2011

Wash water in the mix: Effects on the compressive strength of concrete

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WASH WATER IN THE MIX: EFFECTS ON THE COMPRESSIVE STRENGTH OF CONCRETE

An Abstract of a Dissertation

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

Approved:

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May 2011

ABSTRACT

Beginning with the Water Quality Act of 1987, requirements were put in place to control sediment run off from construction sites, which typically meant silt fences were installed and maintained on job sites. In 2009, when Aggregate Industries was fined $2.7 million by the Environmental Protection Agency (EPA) for poor management of concrete wash water, the disposal of concrete wash water became a significant issue. Following the EPA guidelines, the Minnesota Pollution Control Agency (MPCA) currently allows the dumping of excess concrete on the job sites, but requires control of all water used to wash concrete ready mix trucks, delivery chutes and tools used to finish concrete. Best Management Practices (BMPs) allow for containment of wash water either on the job site in a lined container or returned to the ready mix plant and stored in a lined pond. The BMPs do not suggest the reuse of the waste water. ASTM standards allow for use of concrete mixing water with up to 50,000 parts per million (ppm) suspended solids, which would allow limited reuse of the waste water. The Minnesota Department of Transportation (Mn/DOT) requires potable water in all concrete mixes used on their jobs, which means all waste water must be disposed in some manner. This study was a response to a needs statement from Mn/DOT asking for research on the environmental effects of concrete waste water. It was an investigation into a potential Best Management Practice for reuse of the water used to wash off ready mix trucks, delivery chutes and tools used to finish concrete. The research was a two by two design with two different concrete mixes, each designed to reach 4000 pounds per square inch (psi) at 28 days. One of the concrete mixes was from the American Concrete Institute (ACI) and the other mix

was from the Minnesota Department of Transportation. Two different water sources, tap water and wash water from the settlement pond at the Central Concrete ready mix plant in Mankato, MN were used in the concrete mixes. Each concrete mix was paired with both tap water and wash water, making a total of four groups. Concrete was mixed using ASTM standards for materials, mixing and storage. Three separate batches of concrete were mixed in the laboratory for each group, making a total of five test cylinders per batch and a total of fifteen test cylinders per group. The 60 test cylinders were stored for 28 days in an environmental chamber, keeping both temperature and humidity within the ASTM standards. The cylinders were then tested for compressive strength using standard ASTM methodology. The three batches for each group were analyzed for mean compressive strength, variance and standard deviation within both the batch and the group. Results showed that the group with ACI mix and wash water had the highest mean compressive strength and lowest variability of the four groups. Both the Mn/DOT mix with tap water and the Mn/DOT mix with wash water had lower mean compressive strength than the ACI mixes and also showed higher variability. When compressive strength was analyzed across water source using a two-way ANOVA, the cylinders made with wash water tested at a statistically significant higher mean compressive strength than the cylinders made with tap water. The Eta^2 analysis placed 70% of the variability on the mix design. When the mean compressive strength of the four groups of cylinders was compared using Tukey's HSD, the results showed a statistically significant difference between the wash water and the tap water for each group.

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DEDICATION

This work is dedicated first to my wife Marlys, who has joined me along the way in this incredible journey. Thank you for your unending support.

I also dedicate this work to my parents, Louis and Elaine Wasserman, for the love of learning and the love of life that gave me the confidence to complete this project.

ACKNOWLEDGEMENTS

Thank you to my committee chair, Dr. Varzavand, for working with me on this project. Without his support, this research would have been impossible to complete. Dr. Fahmy, Dr. Gilpin and Dr. Decker, as members of my committee, have always been available and supportive of every effort along the way. Finally, a thank you goes to Dr. Giese, who stepped in to complete the committee and has been a very willing communicator. A big thank you also goes to Dr. Fecik, who opened the Industrial Technology Department to me and allowed me to participate in the program. It has been a wonderful four years of personal and professional growth.

MN State University Mankato has been very supportive of this project. Dean John Knox has encouraged me along the way, allowing me flexibility in scheduling, which gave me time to take classes, learn the fundamentals of research and complete this dissertation. A thank you goes to Dr. Stephen Druschel who encouraged me in the Environmental Lab and was a sounding board when needed during this process. Dr. Scott Fee has been an exceptional mentor, encouraging me to get started on the doctorate and supporting me every step along the way.

The generous support from Central Concrete in Mankato, MN, especially Denny, Pat and Dave, has made this project possible.

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CHAPTER I

INTRODUCTION

Concrete is one of the most common construction materials used in the world. According to the American Concrete Institute (ACI), global annual production of concrete is approximately five billion yards (American Concrete Institute, 2010). The majority of concrete needed for modern building in the United States is delivered by truck after mixing in a batch plant. The exterior of the concrete delivery trucks, the interior of the mixing drum, the chutes used to place the concrete, concrete pumps and tools used in placing and finishing the concrete need to be regularly cleaned in order to prevent the concrete from permanently hardening on the equipment. Cleaning of the equipment is done by spraying water on the concrete residue while it is still wet and washing the equipment until it is clean. The water and concrete mix created through the cleaning process is known as concrete wash water. Wash water includes both the water that is created on the job sites by cleaning equipment and tools and water that is returned to the plant in the mixing drum and then placed in holding ponds.

The most common ingredients in concrete are cement, coarse aggregate, fine aggregate and water. Table 1 lists percentages of each ingredient for a typical mix (Concrete Basics, 2010). The percentages of each material change, depending on the use of the concrete. The cement in the concrete acts as a binder when mixed with water. The cement hardens, or cures, through the process of hydration, a chemical change to the mixture.

Table 1

The most common ingredients in concrete (Concrete Basics, 2010)

Ingredient	Percentage of the Mix
Air	6%
Cement	11%
Coarse aggregate	41%
Fine aggregate	26%
Water	16%

In 2005, 127 million metric tons of cement, produced at 118 cement plants in 38 states, was used to make concrete in the United States. Due to the recession, cement output fell each year from 2006 to 2009. By 2009, the U.S. production of cement had dropped to a total of 73 million metric tons, but was still valued at $8.6 billion. Production of cement was up slightly in 2010, with a forecast for significant growth in the cement industry over the next decade as concrete made from the cement contributes energy savings to the economy (PCA Economic Research, 2010).

Most cement is normal portland cement, often referred to as simply portland cement. Portland cement is made from 80% limestone and 20% clay (Avallone, Baumeister, & Sadegn, 2007). The limestone and clay are heated to 2700 °F to form a clinker. The clinkers are then crushed to form cement powder (Sullivan, 2009).

Aggregates are the sand, gravel and rock added to the cement in the process of making concrete. The Aggregate and Ready Mix Association of Minnesota estimates that 120 tons of aggregate are used in the building of a single home and that 20,000 tons of aggregate are used to build one mile of four lane highway (Aggregate Ready Mix of Minnesota, 2010). Aggregates are divided into coarse aggregate and fine aggregate. Coarse aggregate is either crushed stone or mined rock with common sizes less than ¾" and greater than ¼". Fine aggregate particles are typically smaller than 3/8" and larger than the openings in a #200 sieve, which has a grid with openings of .0029 inches.

Admixtures are chemical compounds added to the concrete mix prior to placing the concrete. Admixtures alter either the properties or the curing time of the concrete (Concrete Basics, 2010). Two materials also considered admixtures are fly ash and slag. Fly ash is a by-product material from coal burning power plants and slag is a by-product material from steel production. The fly ash and slag replace a portion of the cement in the concrete mix but do not significantly affect the properties of the concrete (MnDOT Concrete Manual, 2003).

Approximately 75% of the cement produced in the United States is shipped to ready mix producers. The National Ready Mix Concrete Association (NMRCA) estimates there are 6,000 ready mix plants in the U.S. with around 70,000 delivery trucks. The concrete delivered by the ready mix trucks is estimated to be worth $30 billion per year (Ready Mix Concrete Production Statistics, 2010). The ready mix trucks are loaded at the plant with a dry mix of cement, coarse aggregate and fine aggregate, along with necessary admixtures. Water is added to the mix and the drum of the ready mix truck rotates, mixing the ingredients while traveling to the assigned job site, creating concrete along the way. The cement, combined with the aggregates, admixtures and water is referred to as cementitious material.

Concrete from a ready mix plant has a limited shelf life. Once mixed in a delivery truck, the concrete must be delivered within 90 minutes or it will begin to deteriorate in quality. Once the concrete delivery is completed, the delivery truck, the inside of the delivery truck drum, the chute of the delivery truck, as well as the concrete tools, must be cleaned. The cleaning is done with water carried in a separate 125-150 gallon tank on the ready mix truck.

Environmental Issues with Concrete

Until the passage of the Water Quality Act of 1987 (EPA, 2010), there were no regulations for control of the wash water from concrete operations. Beginning with the 1987 Act, control of sediment from construction sites and concrete operations was required. In 2009, the Department of Justice fined a national ready mix supplier $2.7 million for violations related to the disposal of water and sediment (United States Department of Justice, 2009). Several states, including California, Oregon, Minnesota and Louisiana have adopted regulations intended to control the disposal of concrete wash water, including both water used to wash out the concrete ready mix trucks after delivery and water used to clean tools. Under the Minnesota Pollution Control Agency (MPCA) regulations, the wash water can not touch the ground (Construction Stormwater Permit-NPDES/SDS, 2009).

The current Best Management Practices (BMPs) are either to contain the wash water on the job site and then haul the water to the landfill or to return the water to the delivery truck and haul it back to the ready mix plant. Either way, the ready mix supplier is responsible to ensure containment of the wash water. Ready mix suppliers have always had a wash out area at the plant. The trucks get washed off after loading, after delivery of the load and at the end of the day. It is common to use over 100 gallons of water to wash off the delivery truck after loading at the ready mix plant. Each truck carries 125-150 gallons of water in a portable tank attached to the delivery truck. Much of the water is used to wash the chute after delivery of the load. At the end of the delivery day, the truck drivers wash the drums with over 1000 gallons of water (Kellerhuis, personal communication, May 2010). The water used for washing the trucks goes into the settlement ponds at the ready mix plant and remains to evaporate. If the settlement ponds have too much water or the site has too much rain, then the ponds overflow.

The new regulations have required significant modification to both the delivery trucks and the wash out pits. The water returned to the ready mix plant must go through a series of ponds to allow the cement and aggregate solids to settle. Excess water from the ponds must be disposed in some way. A brief survey of ready mix plants showed disposal into a river (Kloos, personal communication, May 2010), into a quarry (Patrick, personal communication, June 2010) and into a wetland (Christiansen, personal communication, June 2010). Some of the ready mix suppliers charge from $20-$30 per load to haul the water back to the plant (Christiansen, personal communication, June 2010). Other plants are not able to charge for the service, but still must follow the MPCA rules, causing a financial hardship (Patrick, personal communication, June 2010).

There are few references in the literature to the nature of the concrete wash water as it is disposed. A synthesis of research by Chini and Mbwambo (1996) found limited related work by the National Ready Mix Concrete Association (NRMCA), the American Concrete Institute (ACI), The Portland Cement Association (PCA), ASTM (formerly known as the American Society for Testing Materials) and privately funded testing by admixture companies. The synthesis by Chini and Mbwambo suggested further investigation was needed to determine if there are any detrimental effects to the use of concrete made with recycled concrete wash water.

This study was a 2 X 2 factorial design. The compressive strength of concrete made using tap water was compared to the compressive strength of concrete made using wash water. Two concrete mixes were used. Each mix was paired first with tap water and then with wash water. A total of 60 concrete cylinders were made for this study. The cylinders were stored for 28 days in an environmental chamber and then tested for compressive strength.

Statement of Purpose

The purpose of this research is to explore an alternative to the use of tap water in concrete mixes. Reuse of wash water would enable a ready mix company to save significant amounts of water, benefitting both their profitability and the environment.

Statement of Need

The United States Environmental Protection Agency, through the state Pollution Control Agencies, has adopted new regulations for discharge of concrete wash water. Dwayne Stenlund, the Erosion Control Specialist for the Minnesota Department of Transportation (Mn/DOT), submitted a Research Needs Statement for the Mn/DOT FY 2011 Academic Research Program requesting assistance with concrete slurry, wash and loss water mitigation. He states, "Violation of the federal clean water act can result in severe financial penalties and loss of federal funds. The goal is to develop innovative, practical and best value best management practices (BMP) that (1) avoid or minimize the loss of concrete liquids and uncured solids…" (Stenlund, 2009).

Ready mix operations are struggling to find acceptable ways to meet the new regulations. Many small ready mix plants will need to invest $50,000 in new ponds in order to qualify for the Storm Water Pollution Prevention Permit (Kloos, personal communication, May 2010). Outfitting each delivery truck costs the ready mix plant about $1600 (Schmit, personal communication, June 2010). The ability to reuse the wash water would reduce the environmental impact of the ready mix operation as well as save the ready mix plants the costs associated with using approximately 35-50,000 gallons of water each day.

Hypothesis Statement

Ha1: It is hypothesized that there is a statistically significant difference between the compressive strength of concrete made with wash water and the compressive strength of concrete made with tap water.

Ho1: There is no difference between the compressive strength of concrete made with wash water and the compressive strength of concrete made with tap water.

Assumptions

The following assumptions are made by the researcher:

1. Tap water from a single source will not vary significantly in properties and will not affect the properties of the concrete mix.
2. Admixture compounds remaining in the wash water will not affect the properties of the concrete placed in the test cylinders.
3. Holcim Type 1 cement used in the study has been accurately tested by the manufacturer and requires no additional confirmation of either pH or specific gravity.

Limitations

The following limitations are made by the researcher:

1. Two concrete mix designs were used. The mixes were designed to have a compressive strength of 4000 psi at 28 days. The use of other mix designs was beyond the scope of this study.
2. The cement mixer used was a two cubic foot capacity electric mixer. Each batch of concrete filled five test cylinders. Larger volumes of concrete were beyond the scope of this study.
3. Holcim Type 1 portland cement was used in this study. The varying formulations of portland cement were beyond the scope of this study.

4. The water to cement ratio was held constant in each concrete batch by adjusting the water volume according to the moisture content of the concrete and aggregate used in the mix.
5. Central Concrete in Mankato, MN was the single source for tap water and wash water in the study. Additional sources of either tap water or wash water were beyond the scope of this study
6. All test cylinders were 6" X 12" in size and met the specifications of ASTM C470 (ASTM, 2009c). No other sizes of molds were used in this research project.

Delimitations

The following delimitations are made by the researcher:

1. Public policy for Storm Water Pollution Prevention Plans (SWPPP) as they affect concrete waste water was not reviewed.
2. Chemical analysis of tap water from Central Concrete was not conducted as part of this study.
3. Analysis of admixtures and their effects on the compressive strength of the concrete was beyond the scope of this study.
4. The cylinder molds were commercially purchased from a standard supplier and were not further tested.
5. Unbonded caps, commercially purchased and meeting the specifications for ASTM C1231 (ASTM, 2010b), were used in the process of compression testing. The caps were not further tested.

Definitions of Common Terms

Certain terms that were used, although not unique to this study, have been defined in order that readers have a common basis for understanding their use within the context of this research. The definitions of common terms are contained in Appendix A.

CHAPTER II

REVIEW OF LITERATURE

Concrete was first used as a construction material in Roman road building. The Romans used pozzolana, a volcanic ash mixed with lime and water to make a form of concrete. Pozzolana concrete has helped Roman roads last for two millennia (Overman, 1968). After the fall of the Roman Empire, the knowledge of concrete was lost until J. Smeaton researched the Roman use of concrete prior to rebuilding the Eddystone Lighthouse in Cornwall, England. His report was published in 1793. In 1796, J. Parker received a patent for making a product he called "Roman Cement" from natural deposits found near London. Portland cement was patented in 1824 by J. Aspden (Cowan, 1966). Portland cement was made from powdered limestone mixed with clay or shale and then heated to 1500 degrees. After the mixture was cooled, it was ground to a powder. The portland cement name was derived from the island of Portland, England because the powdery mixture looked like the limestone cliffs of the island (Concrete Technology, 2010a). The mixture could easily be made and shipped anywhere in the world. When builders were ready, the portland cement was mixed with two parts sand, four parts aggregate and water to make what we know as concrete. The compressive strength of the concrete was far superior to any man made material since the Roman use of pozzolana (Overman, 1968).

The compressive strength of concrete, measured in pounds per square inch (psi), makes concrete an ideal material for roads, floors and footings. The compressive strength varies with the mix design, which is the proportion of concrete, coarse aggregate, fine aggregate, sand and water. The compressive strength of concrete may be as low as 2,500 psi for residential applications. It is typically 4000-5000 psi for commercial applications and, for some specialty applications, may be as high as 20,000 psi (Nawy, 2009). Although concrete has high compressive strength, it lacks tensile strength, meaning it can not easily stretch without failure. Metal reinforcement wire was first used to improve the tensile strength of concrete in 1867 by Joseph Monier of France (History of Concrete, 2010a). By adding metal reinforcement, uses for concrete expanded to include vertical construction and bridges. The first iron reinforced concrete beams were built for Thaddeus Hyatt before 1877 (Hyatt, 1925). With the building of the Hoover Dam and the Grand Coolie Dam in the 1930's, concrete became the standard building material for large infrastructure projects (History of Concrete, 2010b).

W.K. Hyatt (1925) of the Purdue University Civil Engineering Department, synthesized the early twentieth century research in concrete. Included in the synthesis was a bibliography of concrete research which listed 9425 published articles dating back to 1877. The American Society for Testing Materials (ASTM), the American Concrete Institute (ACI), the Lewis Institute of Chicago and the Portland Cement Association (PCA) were the leading research institutions of the day. ASTM was founded in 1898 by Charles Dudley with a goal of developing standard test specifications for quality control of steel rails used for railroads. ASTM pioneered the committee method, which brought industry, owners and academia together to write specifications agreeable to all three groups. Specifications for cement first appeared in 1902 (A Century of Progress, n.d.). ACI was founded in 1904 with a goal of "advancing concrete knowledge by conducting seminars, managing certification programs, and publishing technical documents" (American Concrete Institute, 2010). Duff Abrams was the Professor in Charge of Laboratory at the Lewis Institute. Abrams was a pioneer in structured testing, including pressure tests (1919), additives to concrete (1924) and mixing waters (1925). The Portland Cement Association was founded in 1916 to represent the cement companies in the United States and Canada. The mission of PCA has been to "Improve and expand the uses of Portland cement and concrete" (Portland Cement Association, 2010)

Cement Production

The cement production process starts with large scale mining of limestone. The limestone is then crushed into baseball size rocks. The rocks are either mixed with water and fed into a kiln in a wet process or are fed straight into a kiln in a dry process. All new cement plants use the dry process method because it consumes less energy to make the cement. The limestone is heated to 2700 °F and rotated in the kilns. The limestone undergoes a chemical change, with some elements burning off. The remaining calcium combines with other elements in the mix. The resulting product is a marble size clinker which then is cooled and ground into powder (How Portland Cement is Made, 2010).

The ingredients of the cement used in concrete mixes vary considerably, even from the same cement factory. The ingredients for the Holcim Type 1 cement purchased at the Home Depot store in Mankato, MN are listed in Material Safety Data Sheet (MSDS) in Table 2.

Table 2

List of ingredients in Holcim Type 1 cement

Ingredient	Percentage range
Tri-calcium silicate	20-70
Di-calcium silicate	10-60
Tetra-calcium-alumino-ferrite	5-15
Calcium sulfate	2-10
Tri-calcium Aluminate	1-15
Magnesium oxide	0-4
Nuisance Dusts	--
Crystalline Silica	0-1
Chromic acid and chromates	Trace
Free crystalline silica, potassium and sodium compounds, cadmium, chromium, nickel, lead, organic compounds, calcium oxide (free lime)	Potential trace amounts

Due to the rigor of the manufacturing process, the specific gravity of the cement is consistent per manufacturer and type of cement produced. It is measured at the manufacturing site and published with the Material Safety Data Sheets (MSDS) for the material. The tests ensure that the moisture content and compressive strength of the finished product, the concrete, meets the expected specifications (Integrated Publishing, 2010).

Table 3 lists the types of cement commonly used today, as specified in ASTM C150 (ASTM, 2009d). The most common is Type I portland cement, with the other types used for specialty applications (Concrete Technology, 2010b).

Table 3

Types of cement

Type of Cement	Application
Type I	Common use, general application
Type II	Use in water or soil with sulfates
Type III	Use when high early strength is needed
Type IV	Use in massive structures like dams to reduce the heat generated by hydration
Type V	Resists chemicals from environment
Type IA, IIA, IIIA	Adds air to mixture to reduce effects of freeze/thaw cycle

Aggregates

Depending on the mix design, aggregates account for 60-75% of the total volume of the concrete (Concrete Basics, 2010). The fine aggregates, often simply called sand, have many characteristics that must be considered in the mix design. Fine aggregate is not uniform in size. A gradation test, known as a sieve test, using ASTM C128 for fine aggregates (ASTM, 2007c) will determine the percentages of each size particle. Figure 1 illustrates a sieve, a simple screen which allows a given size aggregate to pass through the screen and prevents any material larger than the screen openings from getting to the next level. Hand operated sieve screens are stacked in a series and manually shaken. The mechanical shaker system, shown on the right hand photo of Figure 1, processes greater quantities of materials. Quantities of the smallest particles, known as fines, are critical to monitor in order to meet the compressive strength specifications for the concrete.

Figure 1. Sieve screens and a mechanical shaker system for aggregate separation (UNM Civil Engineering, 2010)

The coarse aggregate might be river rock, which has rounded edges, or crushed rock, which is angular. The gradation and type of the aggregate is specified in the concrete mixes in order to ensure the mix meets the expected requirements. The gradation process, similar to gradation of fine aggregates, also uses sieve testing. Procedures from ASTM C127 are used for coarse aggregates (ASTM, 2007b).

Aggregate also affects the water requirements for the concrete. Some aggregates are dry, which then requires additional water be added to the mix. If the aggregate is completely dry, it is referred to as Oven Dry (OD). Ready mix suppliers usually keep the aggregate in a Saturated and Surface Dry (SSD) condition, which means the aggregate can't absorb any more water. In the SSD condition, the aggregate does not absorb additional water but contributes water back to the concrete mix, lessening the amount of additional tap water needed for the mix.

Admixtures

With the expanded use of concrete in building, came the need to work with concrete under a wider variety of conditions. Compounds, known as admixtures, began to be added to the concrete in order to make it more workable. The most common admixtures are water reducers, air entraining admixtures, accelerators and retarders, fly ash and slag (Everything about Concrete, 2010). Table 4 lists the most common admixtures, their chemical makeup and the effect on the concrete mix. Water reducers are used for almost all Mn/DOT mixes in order to enhance the workability of the concrete (Jorgenson, personal communications, August 2010). The air entrainment admixtures are also used in most Mn/DOT mixes to help the concrete better withstand the Minnesota freeze/thaw cycles. Retarders are commonly used in warm climates to slow the curing process of the concrete due to high outdoor temperatures. Retarders allow concrete crews additional time to place and finish the concrete before it sets up. The accelerator admixtures are commonly used in the Minnesota winters in order to speed the setting process of the concrete in spite of very cold temperatures.

Fly ash and slag are commonly included with the admixtures. Fly ash is a powdery material obtained from the smoke stacks of coal burning power plants. Slag is a product obtained from the melting process from steel mills. The fly ash and slag materials are used to replace a portion of the cement in the concrete mix. Mn/DOT allows fly ash to be used from only a few certified power plants (MnDOT Certified Fly Ash Sources, 2010).

Table 4

Common concrete admixtures (W.R. Grace Admixtures, 2010)

Admixture	Chemicals or source	Effect on concrete mix
Water reducer	Ethylene oxide-Propylene oxide copolymer monobutyl ether	Reduce the water to cement ratio in order to increase strength of the concrete
Accelerator	Calcium chlorides	Used in cold weather to reduce the time needed for the concrete to set
Retarders	Calcium lignosulfanate	Used in hot weather to increase the time needed for the concrete to set
Air entrainment	Resin acids, rosin acids, sodium salts	Add microscopic air bubbles to reduce effects of the freeze/thaw cycle
Fly ash	By-product of coal burning power plant	Reduce the need for cement in the mix design
Slag	By-product of steel production	Reduce the need for cement in the mix design

Curing

When portland cement mixes with water a chemical process called hydration begins. The process takes from four to six hours (NRMCA, 2010). During the hydration time, the concrete can be worked into the place desired, finished as needed and held in place through the use of concrete forms. The hydration process generates heat in the concrete. If the upper portions of a concrete slab cool quickly while the lower portions cool slowly, the concrete may crack due to internal tensile stress.

Characteristics of Concrete

Concrete has excellent compressive strength. The strength is measured in pounds per square inch (psi) which is the amount of pressure that can be placed on the material before failure. Residential concrete is designed to have a strength between 2000-3000 psi, while the strength needed for roads is typically in the 3000-4000 psi range. High psi concrete, used for specialty commercial applications, may be over 10,000 psi (Concrete Basics, 2010). The high compressive strength of concrete makes it ideal for roads, where the need is to withstand pressure from traveling vehicles. One of the most significant determining factors for compressive strength of concrete is the water to cement ratio (w/c). Indoor concrete does not have a defined w/c requirement but is typically near .50. Concrete exposed to the corrosion may have a w/c as low as .40 (American Concrete Institute, 2007).

Concrete Mixing

Guidelines from ASTM C192 state that concrete batches should allow for 10% excess after filling the test molds (ASTM, 2007a). When using a machine to mix the sample, the coarse aggregate and some of the mixing water are to be added to the mixer prior to starting rotation of the mixer. Next, the fine aggregate, cement and water are added while the mixer is running. Once the ingredients are all in the mixer, the concrete is to be mixed for three minutes, followed by a three minute rest and then a final two minute mixing. The moisture content of the aggregate supply changes during the course of mixing multiple batches of concrete with a small mixer, which affects both the slump and final compressive strength of the concrete. In order to compensate for differing moisture conditions, the operator must make small adjustments to the amount of water used in each batch. Note 12 of ASTM C192 states, "An experienced operator may add water incrementally during mixing to adjust to the desired slump" (ASTM, 2007a, p. 5).

Field testing of water to cement ratio in the concrete is done using the slump test (Slump Test, 2010). Figure 2 illustrates a field slump test. The concrete is placed into a cylinder in a series of three lifts. The concrete is tamped with a rod 25 times after each lift. After the final lift, the top of the cylinder is struck off to level the concrete. The cylinder is slowly removed. The concrete, without the cylinder to hold it, settles. The number of inches that the concrete "slumps," or settles, is the measure used. The lower the slump number, the stronger the concrete is expected to be when fully cured.

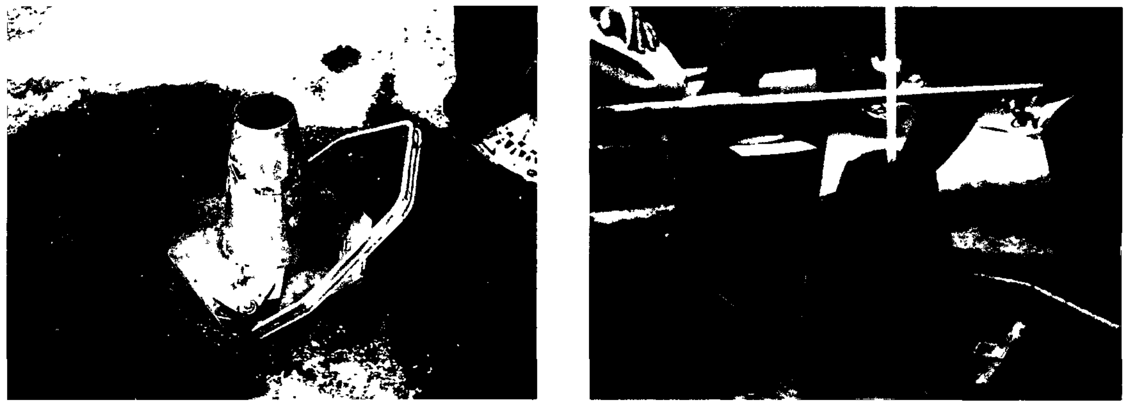

Figure 2. Field Slump Test (UNM Civil Engineering, 2010)

Compressive strength of the concrete is measured in the laboratory using test cylinders cast from the concrete mix. Nawy states the compressive strength of concrete is based on, "standard 6 in. by 12 in. cylinders cured under standard laboratory conditions and tested at a specified rate of loading at 28 days of age" (Nawy, 2009 p. 33). Cylinder molds are either reusable steel forms or single use plastic forms. Specifications for molds are referenced in ASTM C470 (ASTM, 2009c). Molds must have an height that is twice the diameter and be made of a material that does not flex or leak when the concrete is placed in them. The diameter of the mold must be three times the diameter of the largest aggregate, as specified in ASTM C192 (ASTM, 2007a).

Test cylinder samples are filled from concrete obtained from the mix as it is being used on the job. The 6" cylinders are filled to 1/3 height and then rodded in order to consolidate the concrete. The cylinder is then filled to 2/3 height and rodded again. The cylinders are then filled completely, rodded a final time and then the tops are struck off to level with the top of the form. If the concrete is vibrated with a mechanical vibrator, the test cylinders only need two lifts before striking off the tops (ASTM, 2007a).

Cylinder Caps

The test cylinders are then either capped, left uncapped or subjected to grinding in order to level the axial surface. If the cylinders are capped, the exposed cylinder tops receive a ¼" layer of neat portland cement paste in accordance with ASTM C617 (ASTM, 2010a) in order to level the top surface of the cylinder. If the cylinders are left uncapped, an unbonded cap must be used when compression testing occurs, in accordance with ASTM C1231 (ASTM, 2010b). The unbonded caps are made of a neoprene substance which allows the compression load to be evenly distributed when the cylinders are tested. If the axial surfaces of the cylinders are not leveled with either a bonded cap or an unbonded, neoprene cap, the axial surface of the cylinder must be ground to within .002 inches of perpendicular. If one of the three methods are not used on the samples, the hydraulic pressure from the testing machine will be unevenly distributed on the cylinder and the compression test results will be inaccurate.

Cylinder Storage

Test cylinders are stored in a moist room, a "walk-in" storage facility with controlled temperature and humidity. According to ASTM C511, the cylinders must be kept at 73 ±3 °F with a humidity level not less than 50% (ASTM, 2009b). The cylinder molds are to be stripped after 24 hours, in accordance with ASTM C39 (ASTM, 2009e). Stripping of single use, plastic, molds requires the use of a hammer and special chisel that cuts the sides of the mold and releases the newly formed concrete.

If a storage room is not available, the cylinders may also be covered with damp burlap for the duration of the curing time, as stated in ASTM C511 (ASTM, 2009b).

Storage is typically for 28 days, in accordance with ASTM C39 (ASTM, 2009e). There are common practices in industry to test cylinders at seven days, although it is not an ASTM standard.

Cylinder Testing

ASTM C 39 (ASTM, 2009e) addresses standard methodology for compression testing of concrete cylinders. The cylinders are subjected to a regulated axial load on a universal testing machine, which records the amount of pressure required until the point of failure. The testing machine must conform to ASTM E4 (ASTM, 2010c). The load rate must be maintained between 28 and 42 pounds per square inch (psi) per second. The loading rate may be increased during the first half of the testing but the designated loading rate must be maintained for the second half of the testing. The load is applied until the test cylinder displays a well-defined fracture pattern and the load has dropped to 95% of the peak load. The testing machine must be calibrated annually in order to ensure accuracy. Figure 3 shows concrete cylinders and the universal testing machine (UNM Civil Engineering, 2010).

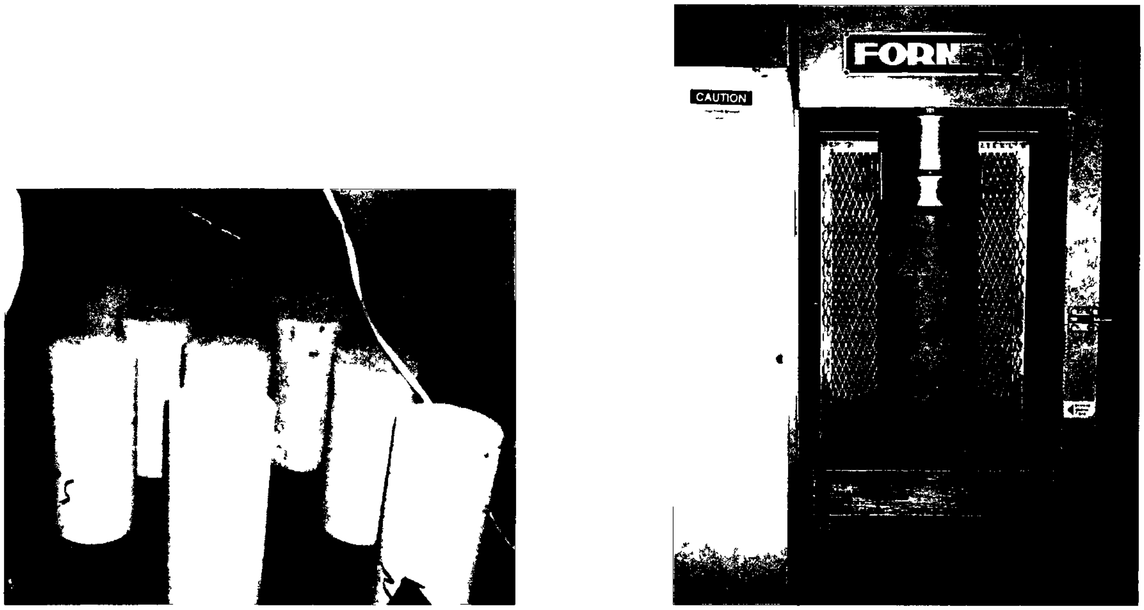

Figure 3. Concrete cylinders and the universal testing machine (UNM Civil Engineering, 2010)

Compression testing results for concrete show considerable variability. According to Steve Bjerke, senior project manager for Old Castle Materials in Mankato, MN, "That's why we constantly test" (Bjerke, personal communication, August 2010). The ACI Manual of Concrete Inspection provides a recommended formula (American Concrete Institute, 2007) for required average test strength of concrete cylinders. The ACI standard is the larger of the two values where f'cr is the required average compressive strength, f'c is the specified compressive strength and SD is the sample standard deviation. The larger result from Equation 1 or Equation 2 gives the required average compressive strength for a group of samples.

$$f'cr = f'c + 1.34SD \tag{1}$$

$$f'cr = f'c + 2.33SD - 500 \tag{2}$$

The results from the universal testing machine are listed as the maximum pounds of load used during the test. The pounds per square inch are calculated by dividing the total pounds of force used by the number of square inches on the axial surface of the test cylinder (ASTM, 2009d). ASTM C670 addresses precision and accuracy of equipment operation. The standard lists the coefficient of variation for a given number of test measurements. The coefficient of variation is an indication of the accepted variation due to the operator of the equipment. Table 5 lists the acceptable range of individual measurements for a given number of tests (ASTM, 2003).

Table 5

Maximum acceptable range of individual measurements

Number of measurements used to obtain a test result	Acceptable range of individual measurements (%)
2	3.9
3	5.7
4	7.3
5	8.6
6	9.9
7	11.0

Fracture patterns for the cylinders are diagramed in ASTM C39 (ASTM, 2009e) and shown in Figure 4. Type 1 cylinder breaks indicate the strongest concrete. Type 3 patterns indicate poor mixing preparation. Types 5 and 6 are cylinders that have not been subjected to compressive testing until full capacity of the cylinders and must continue to be subjected to load. The fracture pattern is not critical to the strength of the concrete. However, if the compressive strength of the concrete is lower than expected, review of the fracture pattern may give a clue to the cause. Of greatest concern is whether the cylinder has large air voids and whether the fracture passes through the coarse aggregate rather than around the aggregate. Fractures of the aggregate indicate a poor quality aggregate was used.

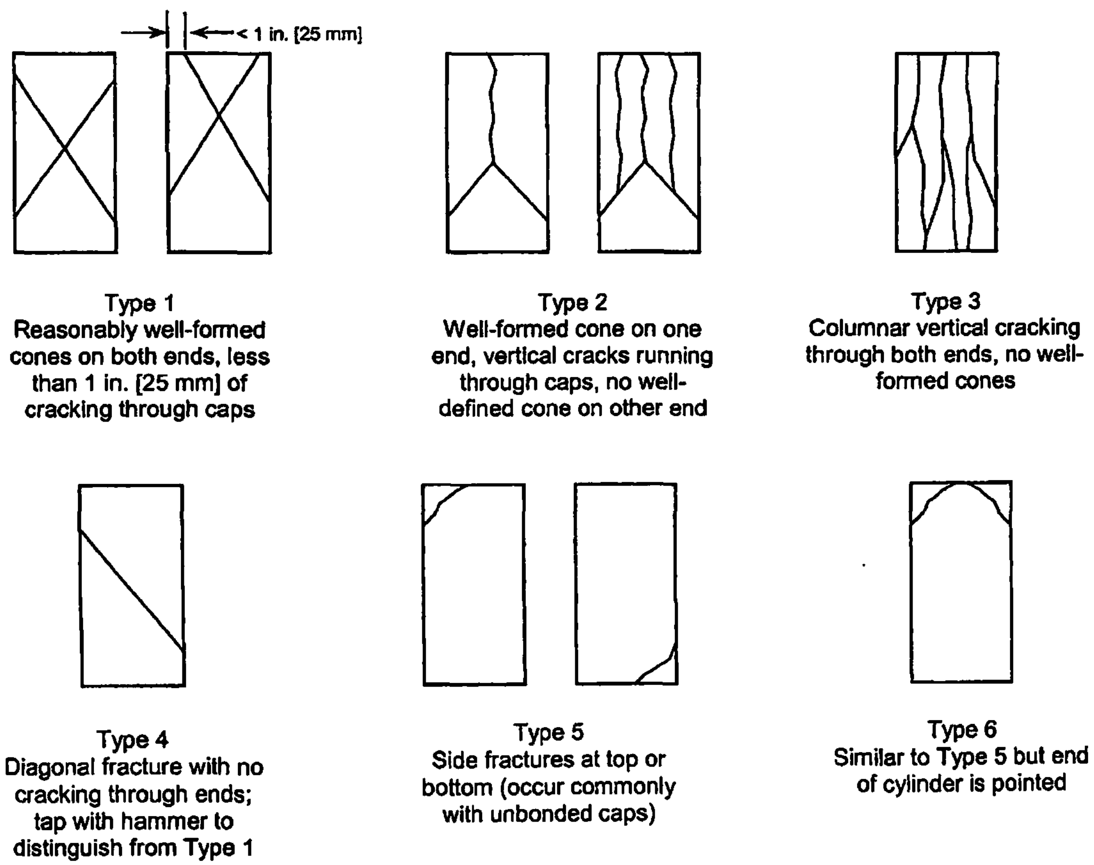

Figure 4. Typical Fracture Patterns (ASTM, 2009e)

Concrete Wash Water

While there is a growing body of regulation from government entities for concrete wash water disposal, there is relatively little reference in research literature to the issue. The environmental concerns are for high pH, total suspended solids (TSS) and total dissolved solids (TDS) in the wash water that may be harmful if discharged into the environment. In addition to the chemicals in the cement formulation, there is a concern for the chemical components in the additives to the concrete mix, including slag, fly ash and other admixtures.

Abrams (1925) tested the compressive strength of concrete after using a wide variety of mixing waters. He used water from the Great Salt Lake, Devil's Lake in North Dakota, Medicine Lake in South Dakota, water from drains and small streams, water containing oil refuse, tannery, soap factory and brewery waste waters, stockyard waste water, paint factory waste water and many other sources. Abrams stated, "The quality of a mixing water is best measured by the ratio of its 28-day concrete or mortar strength to that of similar mixes with fresh water" (1925, p. 2). Compressive strength below 85% of the value for tap water samples was considered unacceptable. The testing results indicated most "impure" waters did not significantly affect the compressive strength of the concrete.

In a study of concrete wash water, Borger (1993) tested recycled wash water in the production of mortar mixes. The wash water used in the mix was created in the laboratory and the mortar mixes contained only cement and sand. Borger found the compressive strength at 28 days was increased by up to 20% when wash water was used in the mix. The key factor was the wash water needed to be less than eight hours old. Borger's recommendations for future study included use of wash water direct from the ready mix trucks and the use of aggregates in test concrete mixes.

Parker and Slimak (1977) evaluated concrete wash water and found pH values typically ranging between 11 and 12. Suspended solids were measured at 100 ppm after sedimentation, but dissolved concentrations ranged from 500 to 2500 ppm, approximately 5 times the level in drinking water. Concrete wash waters were shown as containing sulfates and hydroxides from cement, chlorides from calcium chloride, as well as small quantities of both hydrocarbons and admixture compounds including ethanolamine, diethanolamine, formaldehyde, K-napththalene sulfonte and benzene sulfonic acid. Except for the hydrocarbons and admixture compounds, these values are high but representative of groundwater when in contact with limestone or limestone derived soils.

In a study of soil cement mixes, Bhatty and Kozikowski (2004) found that pH varied by cement content. They found pH levels of 10.5 to 11 for mixes containing up to 9% cement content. The pH generally reduced by one half to one unit in three to five days, with pH levels generally below 9 within 180 days. Bhatty and Kozikowski was the only study found that compared cement treatments across factors of time and cement content for statistical evaluation of composition.

Colin Lobo and others with the National Ready Mixed Concrete Association studied the reuse of concrete without admixtures (Lobo, Guthrie, & Kacker, 1998) and reported that blended concrete could be used where setting characteristics were less critical. Blended concrete using 50% wash water that was three to six hours old showed dramatically reduced compressive strength. The same authors studied the reuse of plastic concrete by using set-retarding admixtures (Lobo, Guthrie, & Kacker, 1995). Preliminary results demonstrated that the use of a 5% mixture of stabilized truck-mixer wash water did not significantly affect the resulting concrete. Their conclusions included, "It is clear that a significant amount of preliminary testing is necessary to effectively use these admixtures to recycle plastic concrete" (1995, p. 14). Lobo and Mullings (1998), in a study of the use of recycled mixer wash water noted that ASTM C94, the standard for ready mixed concrete, allows 50,000 parts per million (ppm) of total solids. Their conclusions demonstrated that when recycled water is used in the concrete mix and the solids content does not exceed the ASTM limits, the strength of the concrete was unaffected.

Environmental Regulations

The Clean Water Act of 1977, updated by the Water Quality Act of 1987, requires control of sediment from construction sites and concrete operations (Effluent Limitation Guidelines, 2010). The documents specifically address point source pollution, meaning the source of the discharge is specific to one incident (NPDES Construction Permits, 2010). The Department of Justice (DOJ) brought a case against Aggregate Industries NE, a national ready mix operation, in which a settlement of $2.75 million was negotiated without the admission of guilt on the part of Aggregate Industries NE (United States Department of Justice, 2009). According to the DOJ decision, the individual ready mix plant, being the point source of the violation, is responsible for the management of concrete wash water waste. If the contractor refuses to provide a proper disposal method for the material, the ready mix driver must return the waste material to the plant (Kloos, personal communication, May 2010).

The Minnesota Pollution Control Agency (MPCA) has modified regulations affecting the concrete and construction industries. On August 1st, 2008, the MPCA approved the reissuance of the General Permit for Authorization to Discharge Stormwater Associated with Construction Activity (Construction Activity Permit). A major change in this permit affecting ready mix concrete deliveries in the state of Minnesota is the section pertaining to concrete wash water (Construction Stormwater Permit-NPDES/SDS, 2009). The Construction Activity Permit does not allow any concrete chute rinse water or water used to wash off concrete tools to come into contact with the ground. Excess concrete from forms, pumps, and chutes may come into contact with the ground as long as they are disposed in accordance with MPCA regulations when in a hardened state (Concrete Washout Guidance, 2009). The Best Management Practices (BMPs) suggested by the MPCA are removal of excess water, capture of all sediments and removal or proper beneficial use of hardened solids. MPCA further states:

> Hardened solids can be removed whole or broken up first depending on the type of equipment available on site. In accordance with Minn. R. 7035.2860, subp. 4, item I; the hardened concrete can be used as a substitute for conventional aggregate. If the material is not utilized in accordance with the standing beneficial use determination referenced above, up to 0.5 cubic yards of concrete washout solids may be managed on-site. If concrete washout solids are buried on site, they should be at least two feet below the surface and must not be buried in the groundwater table. Quantities larger than 0.5 cubic yards of concrete washout solids must either be managed with the rest of the sites solid wastes or obtain an approval from the MPCA's solid waste program for other beneficial use options (Concrete Washout Guidance, 2009, p. 2).

Two states have similarly developed BMPs and requirements for management of concrete waste. WM-8 of California Stormwater Quality Association (California Stormwater BMP Handbook, 2003) and NS-14 of Oregon Department of Environmental Quality (Oregon Department of Environmental Quality, 2005) include both regulations prohibiting discharge of concrete wash water and suggested practices for contractors to follow. Louisiana has only requirements in place without developed BMPs (Louisiana Department of Environmental Quality, 2009).

Best Management Practices

The United States Environmental Protection Agency (EPA) lists several best management practices for concrete wash water (NPDES Concrete Washout, 2009). Included are both on site disposal and off-site disposal recommendations.

There are several commercial systems of water-tight bins that are available for disposal of wash water on the job sites. Drivers from the ready mix trucks wash the chutes and drums and release the water with the concrete waste into the bin. When the bin is full, the water is pumped out and sent to a disposal site. After drying the sediment contained in the bin, the sediment is removed and the bin is then returned to service.

Another BMP concept is to build a containment system from hay bales and a plastic liner. The concept is similar to the commercial dumpster but is less expensive for a contractor. After the solids settle, the water is pumped out and the material can then be disposed by the same methods as any solid concrete (Concrete Washout, 2010).

Many concrete trucks are being outfitted with wash water return systems (AVR Concrete, 2010). The photo in Figure 5 shows a customized return system installed at Apple Valley Ready Mix (AVR Concrete, 2010). The amount of water used in truck washing has some variability, due to individual drivers and concrete mixes. Each delivery truck carries 125-150 gallons of water to be used as wash water on the job site. By the time the delivery truck is ready for the next load, approximately 500 gallons of water are used (Kloos, personal communicaton, May 2010).

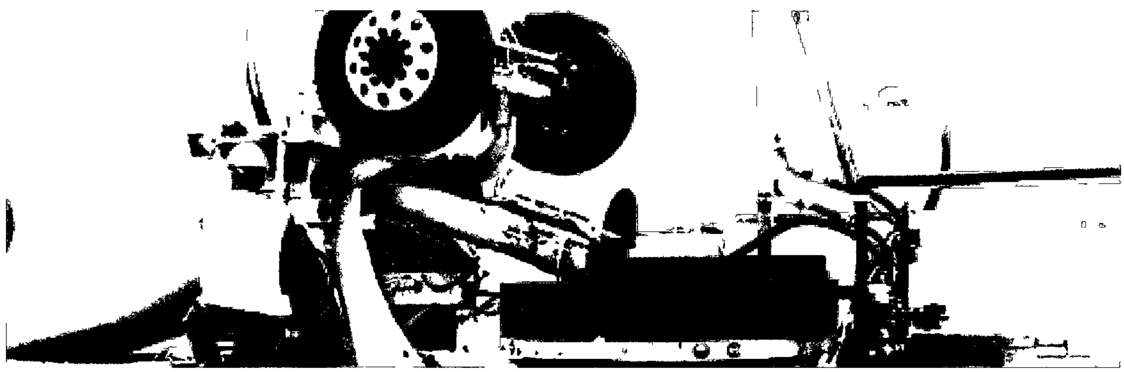

Figure 5. Wash water return system at Apple Valley Ready Mix (AVR Concrete, 2010)

The wash water return systems collect the water at the end of the chute. Some systems filter the material for sand and aggregate, which can be legally dumped on the job site. The remaining slurry is pumped back into the drum of the truck and returned to the plant. Back at the ready mix plant, the slurry is dumped into the wash water pond system. Other truck mounted systems collect both the wash water and the slurry and return the entire contents to the drum, where it is transported back to the plant. Back at the plant, the material is dumped into an extractor, where the sand and aggregate are removed. The remaining material is then sent to the wash water pond system. Figure 6 is a photo of the extractor at Central Concrete in Mankato, MN and the photo in Figure 7 shows the sand after separation from the extractor.

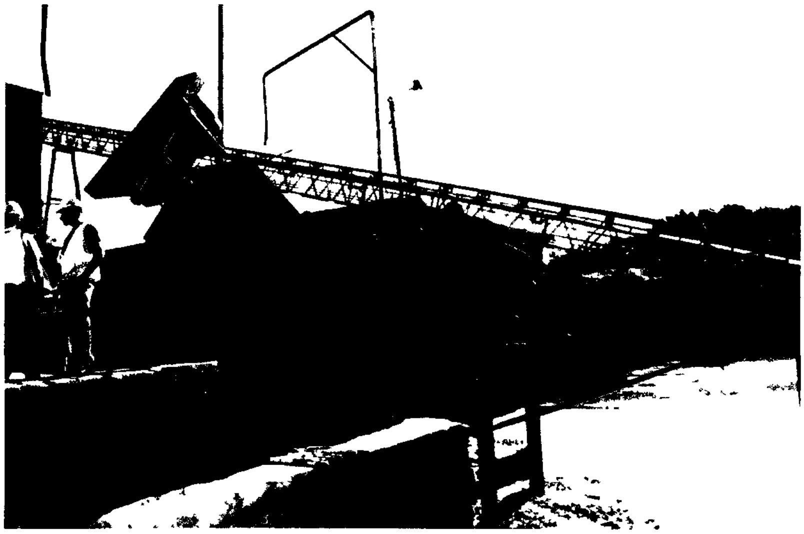

Figure 6. Extractor at Central Concrete in Mankato, MN

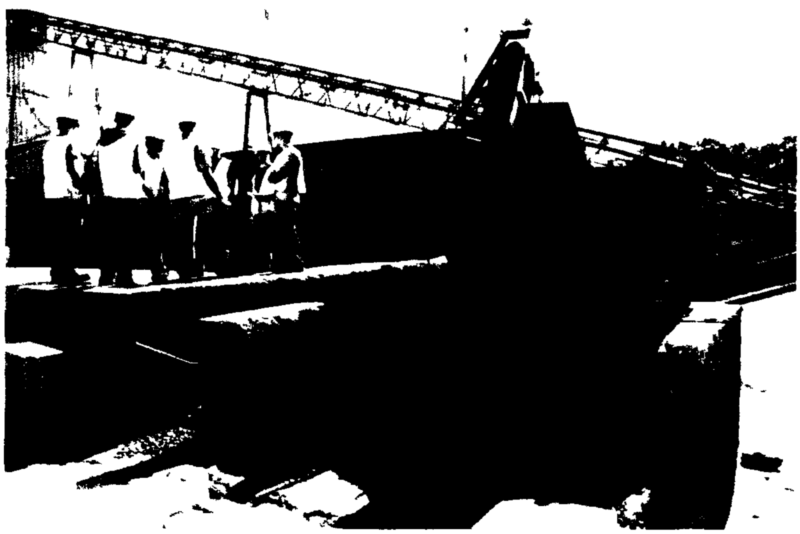

Figure 7. Sand after extraction

Traditionally, ready mix plants have had a pit at the rear of their property where the drivers would wash out their trucks and dump their waste water. The current enforcement levels for concrete wash water have dictated a change to both policy and procedure for ready mix operations. Plants are required to manage the increased amounts of returned wash water using a concrete lined settlement pond. The wash water pond in Figure 8, located at Duluth Ready Mix, is concrete lined, meeting current regulations.

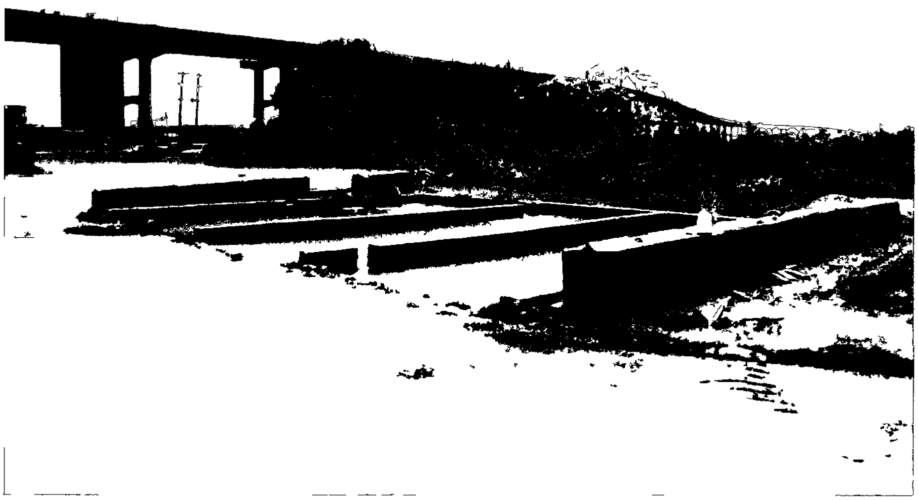

Figure 8. Settlement pond at Duluth Ready Mix

Some plants are choosing a weir system (Weir, 2010) to manage the increased amount of water. A weir system creates multiple settlement ponds for the water. When the first pond is full, the overflow goes to a second pond and then on to a third pond. Most of the suspended solids are left in the first pond. When the ponds become full of solids, the water must be pumped and the solids are then scooped out with a loader and dried. The material then can be disposed or reused (Kloos, personal communication, May 2010).

Current BMPs do not include the reuse of the concrete wash water from a ready mix delivery truck or the reuse of water that has had the solids removed through either filtration or sedimentation. The Minnesota Department of Transportation (Mn/DOT) specifically prohibits the use of such material in all concrete mixes used on Mn/DOT projects (MnDOT Concrete Manual, 2003).

Reuse of the wash water in the concrete mix would create a best management practice that would help mitigate what the EPA has determined to be a serious pollution problem.

CHAPTER III

METHODOLOGY

This chapter provides an overview of the experimental research design to determine whether the use of concrete wash water affects the compressive strength of concrete. This two by two study, using two concrete mixes and two types of mixing water, was designed to compare the compressive strength of concrete when tap water was used in the mix to the compressive strength of concrete when wash water was used in the mix. The two concrete mixes were independent variables. The concrete mixes were labeled either ACI mix or Mn/DOT mix. Each of the concrete mixes was then paired with two additional independent variables, tap water and wash water, creating four groups to study. The dependent variable was the compressive strength of the cylinders that were made with the four possible combinations of the mixes and waters. The compressive strength data were analyzed using a two-way ANOVA procedure.

ASTM standard methodologies were used to prepare and test the necessary materials as well as mix the concrete, make the test specimens and test the concrete cylinders after curing.

Material Selection and Preparation

Test cylinders conforming to ASTM C470 (ASTM, 2009b) were used as molds for the study. The test cylinders were round, with a diameter of 6" and a height of 12". Each mold contained a total of 339 cubic inches of concrete when filled. An electric concrete mixer with a 2 cubic foot capacity was used to mix the concrete. Quantities of the materials were adjusted to 5% of a cubic yard, yielding 1.35 cubic foot batches of concrete. Each batch of concrete yielded five test cylinders. A total of 60 cylinders were made. There were 30 cylinders made using mix 1, labeled ACI mix, and 30 cylinders made using mix 2, labeled Mn/DOT mix. Both the ACI mix design and the Mn/DOT mix design, with quantities needed to mix one cubic yard of concrete, are listed in Appendix D. Half of the cylinders for each mix design were filled with concrete mixed using tap water and the other half were filled with concrete mixed using wash water. Table 6 shows the number of test cylinders for each group.

Table 6

Test groups for concrete mixes

Group Name	Code Used	Quantity
Mix 1 with tap water	AT	15
Mix 1 with wash water	AP	15
Mix 2 with tap water	MT	15
Mix 2 with wash water	MP	15

The cement used in all the concrete mixes was Holcim Type 1 portland cement obtained from the local Home Depot store in 92.6 pound bags. Holcim cement is designed to meet ASTM C150 (ASTM, 2009d). The Material Safety Data Sheet (MSDS) for Holcim Type 1 cement lists the pH as 12-13 and the specific gravity as 3.15 (Holcim Material Safety Data Sheet, 2009).

The admixtures used in the Mn/DOT concrete mix included water reducer, air entrainment and fly ash. The water reducer was from General Technology Resources (GRT) and labeled as GRT KB 1000 (General Technology Resources/kb-1000, 2010) and is measured per hundred weight of the cementitious material, meaning the combined weight of the cement and fly ash. The air entrainment admixture was also obtained from GRT and labeled PolyChem VR air (General Technology Resources/VR Air, 2010). The fly ash was Mn/DOT approved and obtained from the Coal Creek power plant in North Dakota (MN-DOT Certified Fly Ash Sources, 2010).

Central Concrete in Mankato, MN was the source for both the coarse aggregates and fine aggregates. Appendix XI of ASTM D75 (ASTM, 2009a) was used as a guideline for the sampling. The non-mandatory information contained in the appendix suggests sampling from three locations in the stockpile, one portion from the top third of the pile, one portion from the middle third and one portion from the bottom third of the stockpile. The reason for the varied locations of sampling is to randomize the sample, keeping the sample as representative of the entire stockpile as possible. Figure 9 shows the typical collection method for the aggregate materials. The aggregate material was shoveled into 5 gallon pails. All aggregates were collected on the same day and at the same time of day in order to ensure consistent control of moisture. The pails were covered until the aggregate was used in the concrete mix, again helping to mitigate the potential moisture loss which could occur when the material was stored in the laboratory.

Figure 9. Collection of 1" minus Sioux Rock aggregate from Central Concrete

The coarse aggregate was labeled 1" minus washed quartz. The term 1" minus simply refers to the maximum size of the aggregate. The aggregate was mined, crushed and washed at the Sioux Rock Products pit in Comfrey, MN. A sample of the rock was sieve tested at the pit and the results are listed in Table 7. Results are measured as a percentage of the material which passes through the sieve size. All of the rock passed the 1" sieve and only .1% of the rock passed through the #200 sieve. The pit tests showed the rock evenly distributed in size between the 3/4, 1/2, 3/8 and #4 sieve sizes. Material passing the #200 sieve is labeled as fines and is a detriment to the concrete mix. The sample met the Mn/DOT quality standards for concrete aggregate.

Table 7

Sioux Rock pit sieve test results for 1" minus aggregate

Sieve size	% of sample passing	Mn/DOT Standard
1"	100	100
¾"	93	85-100
½"	58	
3/8"	39	30-60
#4	6.2	0-10
#8	.4	
#16	.3	
#30	.2	
#50	.2	
#100	.1	
#200	.1	0-1

The fine aggregate was washed concrete sand from the North Star pit near St. Peter, MN. A 673.9 g sample of the fine aggregate was tested at the pit and met Mn/DOT acceptance levels. The North Star pit analysis showed 100% passed the 3/8" sieve and only .2g passed the #200 sieve. Over 40% of the sand passed through the #30 sieve size and was not able to pass through the #50 size. The fineness modulus was calculated by adding the cumulative % retained on sieve sizes #4, #8, #16, #30, #50 and #100 and dividing the total by 100. By using the formula, the fineness modulus was calculated to be 2.747. The North Star pit sieve test results are in Table 8.

Table 8

North Star pit sieve test results for concrete sand

Sieve size	Weight retained (in grams)	% of sample passing	Mn/DOT standard	Cumulative % retained
3/8”	0	100	100	0
#4	3.8	99.4	95-100	0.6
#8	68.9	89.2	80-100	10.2
#16	83.6	76.8	55-85	22.8
#30	177.7	50.4	30-60	49.6
#50	279.0	8.9	5-30	91.0
#100	55.6	.6	0-10	99.2
#200	4.0	0	0-2.5	
Pan	.2			
Fineness Modulus				2.734

Mix Water

ASTM standards for mixing waters are addressed in ASTM C1602. The water must contain fewer than 50,000 parts per million (ppm) of suspended solids (ASTM, 2006a). Mn/DOT requires the use of potable water in all concrete mixes (MnDOT Concrete Manual, 2003) even though ASTM standards permit other waters to be used.

The city of Mankato water quality results from the November 2009 testing at the Mound Ave Water Treatment Plant are listed in Table 9 (Oconnell, 2009). Tap water has no measurable Total Suspended Solids (TSS) and is used as the comparative standard when testing for turbidity, or cloudiness of the water.

Table 9

Mound Ave Water Treatment Plant laboratory results

Analyte	Results	Recommended Allowable Limit
pH	8.6	6.5
Total Dissolved Solids	257 mg/L	500 mg/L
Total Hardness	197 mg/L	N/A

Central Concrete was the source for both tap water and concrete wash water used in the mixes. Central Concrete uses the Mankato, MN city water supply. Tap water was obtained from the hose that supplies the trucks. The wash water was scooped from the settlement ponds using a one liter container attached to the end of a sixteen foot pole. The pond samples came from near the water surface and from multiple locations within the pond, as shown in Figure 10.

The researcher chose to use wash water from the settlement pond at Central Concrete rather than water directly from the chute of a delivery truck to improve the consistency of the water used in the mix and to ensure that the suspended solids remained below the ASTM standard of 50,000 ppm.

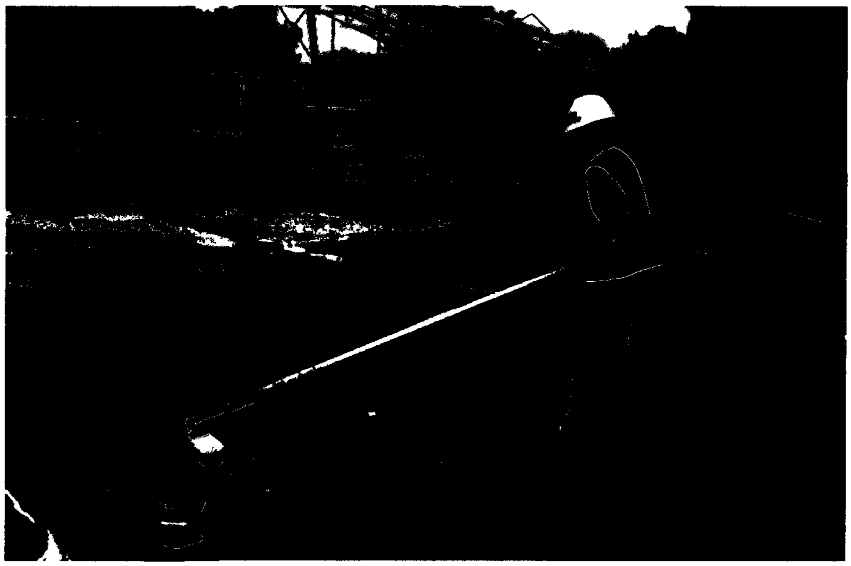

Figure 10. Wash water samples taken from Central Concrete

Both the tap water and the wash water were tested for ph, total suspended solids, turbidity and total dissolved solids. Table 10 lists the tests, along with a brief explanation and the ASTM standard used for testing. The pH testing was used to determine acidity or alkalinity of the water. High pH levels are an environmental concern with concrete wash water. It is unknown whether the high pH levels of water used in the mix will affect the compressive strength of the concrete. Total Suspended Solids (TSS) is the measure of large particles floating in the water. The wash water, due to the cement and fine aggregates, was expected to have high levels of TSS. The suspended solids must be kept under 50,000 ppm according to ASTM guidelines. The turbidity of the water is a measure of the small particles that cause the water to be cloudy. Turbidity has not been researched for any potential effect on the compressive strength of concrete. The Total Dissolved Solids (TDS) are substances that are too small to be filtered out of the water but remain after evaporation of the water. Potential dissolved solids include traces of admixtures used in previous batches of concrete.

Table 10

List of tests used for both tap water and wash water

Test	Description	ASTM Standard
pH	Measure of alkalinity or acidity	D1293-99
Total Suspended Solids	Solids that are visible and will settle out of the water	D3977-97
Turbidity	Cloudiness of the water caused by particles that are too small to be seen	D6855-03
Total Dissolved Solids	Particles that will not settle out of the water	D3977-97

The testing for pH followed ASTM D1293 (ASTM, 1999). A HACH HQ 40d pH meter was used for testing samples of both settlement pond water from Central Concrete and tap water from the Mankato city water supply. Calibration of the equipment was accomplished through automatic calibration using standard known solutions with a defined pH. Samples of the waters were placed in small beakers and the pH probe was placed in the water. The meter directly read the pH levels for the samples.

Standards for the total suspended solids and total dissolved solids are addressed in ASTM D3977 (ASTM, 1997). Measured volumes of samples were filtered and then decanted. The filtered material was dried in an oven overnight and then cooled in a dessicator. The dry material was weighed and was compared to the wieght of water in the sample for a measure of total suspended solids. The remaining water was used for measuring total dissolved solids. The filtered samples were oven dried until all water was evaporated. The remaining material was weighed and compared to the original weight of the sample for a measure of total dissolved solids.

ASTM C6855 was used as a guide for testing the turbidity of both the tap water and the wash water (ASTM, 2010e). Turbidity, or the cloudiness of the water, is measured by the intensity of scattered light (Turbidity, 2010). The measured intensity is compared to the intensity of scattered light when using tap water as the sample. Turbidity was measured using an Oakton T-100 turbidimeter.

Sample Preparation

Two concrete mix designs were chosen for the experiment. The first design was from ACI and used only portland cement, aggregate, sand and water (Ghaly & Almstead, 2010). The concrete was designed for a compressive strength of 4000 PSI at 28 days with a slump of 1-4" when tested immediately after mixing. Appendix D shows the ACI mix design quantities for one cubic yard of concrete, obtained by using the Ghaly & Almstead (2010) web site calculations as a guide. Table 11 lists the materials used in the ACI design with the specified quantities per cubic yard and the quantities actually used per batch of concrete mixed. The water to cement ratio (w/c) of the mix design was .53, with 316.2 pounds of water and 596.5 pounds of cement used for each cubic yard of concrete mixed. Aggregate in the mix is calculated using the OD measure, which required the addition of approximately 3% more water in the mix.

Table 11

ACI mix design

Material	Quantity in pounds per cubic yard	Quantity in pounds per batch mixed
Aggregate	1736.6	86.8
Sand	1235.9	61.8
Water	316.2	15.8
Portland cement	596.5	29.8

w/c ratio=.53

The ACI samples were mixed on a single day. The water type was rotated with each batch mixed. Batches 1, 3 and 5 used the ACI mix and Tap water, batches 2, 4 and 6 used the ACI mix and wash water. The rotation was designed to mitigate any effect that the drying of the aggregates could possibly have on the experimental results.

The second mix design was a Mn/DOT certified mix used on a street in New Ulm, MN (Jorgenson, personal communication, August 2010). The Mn/DOT mix was designed to meet 4000 PSI strength at 28 days. The designed slump for the mix was 1-3" and used a water reducing admixture to help keep the workability better while reducing the water content. The Mn/DOT approved mix design also included fly ash, which replaced a portion of the cement and an air entrainment admixture. The original mix design, approved by Mn/DOT and obtained through Central Concrete, is listed in Appendix D. Table 12 lists the ingredients for both a cubic yard and a single batch. The water to cement ratio was .40 with 29.05 gallons, or 242.57 pounds of water, 519 pounds of cement and 92 pounds of fly ash used for each cubic yard of concrete mixed.

Table 12

Mn/DOT mix design used on a New Ulm, MN street

Material	Quantity in pounds per cubic yard	Quantity in pounds per batch mixed
Aggregate	1750 lbs	87.5 lbs
Sand	1150 lbs	57.5 lbs
Water	29.05 gal	1.45 gal
Cement	519 lbs	25.95 lbs
Fly ash	92 lbs	4.6 lbs
Air entrainment	7 oz	.35 oz
Water reducer	4 oz/100 wt	.2 oz/100 wt

w/c ratio=.40 using 8.35 lbs/gal of water and SSD aggregates

The Mn/DOT mix cylinders were also cast in one day. The batches were rotated between tap water and wash water. Batches 1, 3 and 5 were Mn/DOT mix using wash water and batches 2, 4 and 6 were Mn/DOT mix using tap water.

Procedures from ASTM C192 were followed for the preparation of the concrete samples. The coarse aggregate and some of the water were added to the mixer prior to starting rotation. The mixer was started and the remaining dry materials were added. Once all materials were placed in the mixer, the batch was mixed for three minutes, followed by a three minute rest and then mixed an additional two minutes. The remaining water was added incrementally to the mix, allowing the operator to adjust the total volume of water to meet the required slump (ASTM, 2007a). Once mixed, the concrete was dumped into a damp mixing pan.

A slump test was performed using ASTM C143 (ASTM, 2010f) for each batch of concrete mixed in order to provide an advance indication of the final compressive strength of the concrete. The material used for the slump test was returned to the mix. Five cylinders meeting ASTM C470 (ASTM, 2009c) were then filled in a series of two lifts. A portable vibrator was used for compaction after each lift as the cylinders were filled, as shown in Figure 11. Two insertions of the internal vibrator were used for each lift.

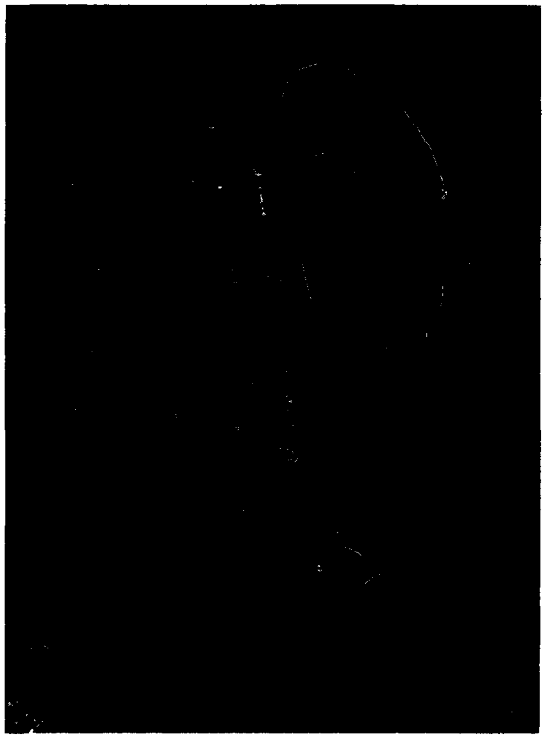

Figure 11. Vibrating each cylinder for compaction

When the cylinders had been vibrated for the final time and were completely full, the tops were struck off. The cylinders were then covered using plastic cylinder mold covers and stored in a moist room meeting ASTM C511 standards (ASTM, 2009b). The photo in Figure 12 shows the moist room. The molds were removed after the cylinders had been in the moist room for 24 hours.

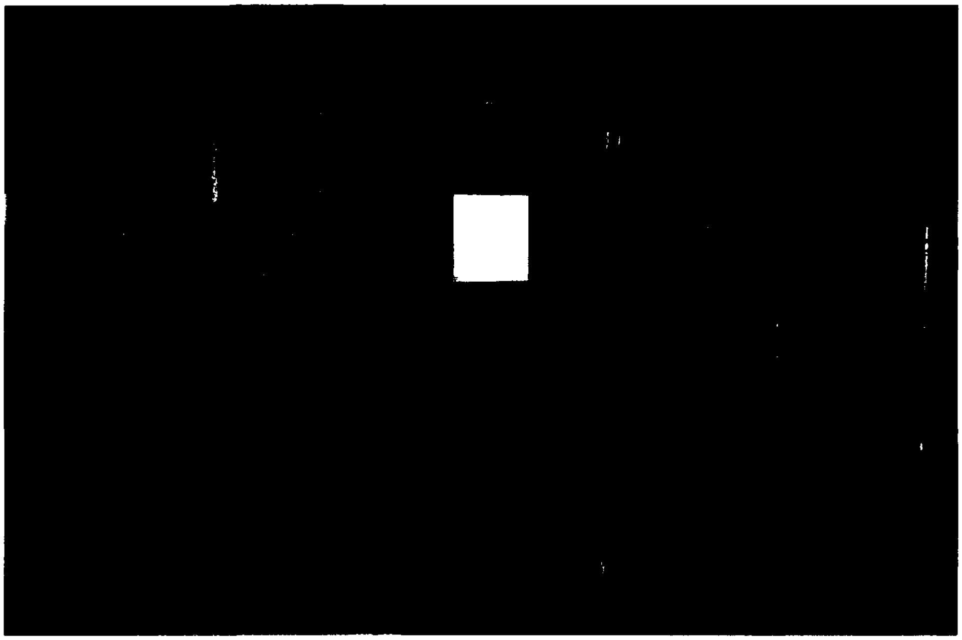

Figure 12. Cylinders were placed in the moist room

Compression Testing

After 28 days, the cylinders were removed from the moist room. The cylinders were placed, one at a time, in the Forney compression testing machine as shown in Figure 13. The compression test was performed according to ASTM C39 (ASTM, 2009e). The machine was calibrated on June 11, 2010 and is scheduled for recalibration in one year.

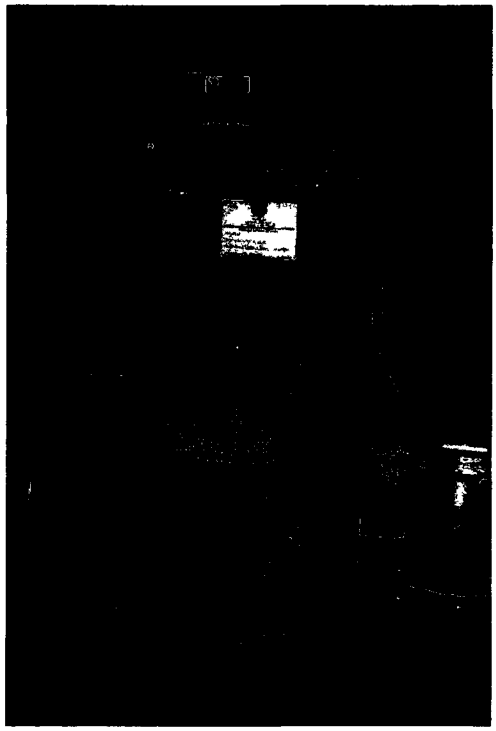

Figure 13. Forney compression testing machine.

The results from the compression test are given in maximum pounds of pressure until failure of the cylinder. The unit for compression testing is traditionally given in pounds per square inch (psi). The psi for each cylinder was calculated by dividing the total pressure applied to the sample by the cross sectional surface area subjected to compression. The cross sectional area of each cylinder was 28.26 cubic inches, so the machine read out was divided by 28.26 in order to correctly calculate the pounds per square inch. Figure 14 shows a test cylinder after failure. The cylinder had a Type 1 fracture, with cone shapes on both the top section and the bottom section.

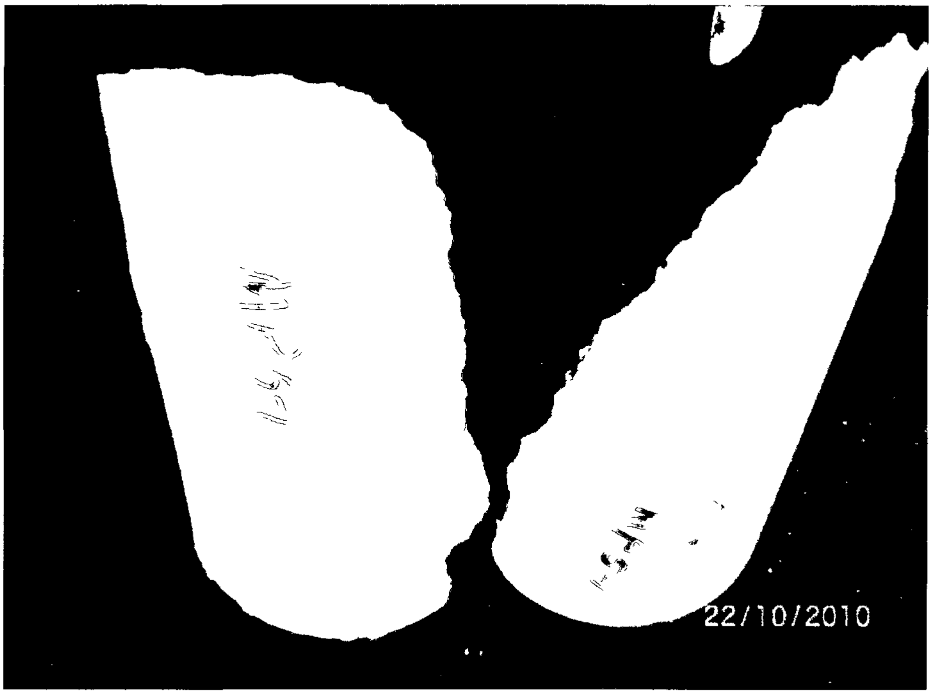

Figure 14. Type 1 fracture, cones on both top and bottom sections of the cylinder

Data Analysis

Data were first analyzed for descriptive statistics. The mean compressive strength for individual cylinders and the mean compressive strength for each batch of cylinders were determined and compared. Ranges, variance and standard deviations were determined for each batch of cylinders. Results for slump tests, pH tests, total dissolved solids tests, total suspended solids tests, and turbidity tests were reviewed for both means and standard deviations. Data were then grouped, first by batch, then by mix design and finally by water source. The grouped data were also analyzed for descriptive statistics.

The data were then subjected to a two-way analysis of variance (ANOVA), which was used to analyze the relationships between two independent variables, each with two levels, and a dependent variable which was both quantitative and continuous. In this experiment, the independent variables were water source and mix design. The independent variable of water source had two levels, wash water and tap water. The independent variable of mix design also had two levels, ACI mix and Mn/DOT mix. The dependent variable was compressive strength, a quantitative and continuous variable. The two-way ANOVA allowed the analysis of the main effect of water source collapsed across mix design as well as the main effect of mix design collapsed across water source. The third issue addressed was the interaction between the two independent variables (Jaccard & Becker, 2002). Alpha levels were set at .05 for the analysis, meaning there was a 5% chance of rejecting the null hypothesis when it was actually true (Box, Hunter & Hunter, 2005). Eta^2 was used to determine the strength of relationship and assign the variability. Finally, Tukey's HSD was used to compute the critical difference and decide whether to reject, or fail to reject, the null hypothesis.

CHAPTER IV

EXPERIMENTAL RESULTS

Aggregate Analysis

The coarse aggregate used in the experiment was 1" minus washed quartz from the Sioux Rock Products pit in Comfrey, MN. A sample of the rock was sieve tested at the pit. The pit test results are shown as percent retained on a given sieve. The results are listed in Table 14. All of the rock is less than 1" and since it is washed, there are minimal fines, material which would pass through the #200 sieve. The pit tests shows the rock evenly distributed in size between the 3/4, 1/2, 3/8 and #4 sieve sizes. A 2.68 pound sample of the coarse aggregate was oven dried and then sieve tested in the laboratory using procedures from ASTM C136 (ASTM, 2006b). The test was conducted using the hand sieve method. Results are also shown in Table 13. Due to availability, there was no 3/8" sieve size used in the laboratory test. The lab test showed the aggregate to be evenly distributed between the sizes tested. The coarse aggregate met the ASTM C33 specification for aggregate (ASTM, 2008) and the Mn/DOT gradation specifications for 1" minus aggregate (MnDOT Concrete Manual, 2003).

Table 13

Pit test and laboratory sieve test results for 1" minus aggregate

Sieve size	Pit test % of sample retained	Lab test % of sample retained	Mn/DOT Standard cumulative % retained
1"	.3	.5	0
¾"	23.4	20.4	0-15
½"	37.4	30.6	
3/8"	16.5	Not Available	40-70
#4	17.0	36.1	90-100
#8	5.1	11.8	
#200		.1	0-1

The fine aggregate was washed concrete sand from the North Star pit near St. Peter, MN. A 673.9 g sample of the fine aggregate was tested at the pit. The pit test results are shown as the percent passing through the sieve. The North Star pit analysis showed 100% of the material passed the 3/8" sieve and only .2g passed the #200 sieve. Over 40% of the sand passed through the #30 sieve size and was not able to pass through the #50 size. The material yielded a fineness modulus of 2.73. A sample of the fine aggregate was oven dried and sieve tested in the laboratory. Gradation testing was conducted according to ASTM C128 (ASTM, 2007c). The lab results were consistent with the pit test results, with 65.6% of the material retained at the #30 and #50 sieve sizes. The fineness modulus of the lab tested sample was calculated by adding the cumulative percent retained on sieve sizes #4, #8, #16, #30, #50 and #100 and then dividing by 100. The lab sample fineness modulus was 2.485. The results of both the North Star Pit testing and the laboratory testing are shown in Table 14.

Table 14

Laboratory sieve test results for concrete sand

Sieve size	Pit Tests % of sample passing	Lab Tests% of sample passing	Mn/DOT standard
3/8"	100	Not Available	100
#4	99.4	99.8	95-100
#8	89.2	90.1	80-100
#16	76.8	77.7	55-85
#30	50.4	43.7	30-60
#50	8.9	12.1	5-30
#100	.6	4.5	0-10
#200	0	.1	0-2.5
Fineness Modulus	2.734	2.485	

The moisture content of the coarse aggregate was analyzed according to ASTM C127 (ASTM, 2007b) and the fine aggregate analyzed according to ASTM C128 (ASTM, 2007c). Results for the moisture content of both coarse aggregate and fine aggregate are contained in Table 15. The aggregates from Central Concrete were kept in Saturated Surface Dry (SSD) condition. After mixing test batches of concrete in the lab, it was determined that, due to the SSD condition of the aggregates, the aggregate supplied approximately 2% of the total water needed for the mixes. The percent moisture was calculated by subtracting the OD mass from the SSD mass and dividing the result by the OD mass, as stated in formula 3.

$$\text{Percent moisture} = (\text{weight wet} - \text{weight dry})/\text{weight dry} \times 100 \tag{3}$$

For coarse aggregate, the formula resulted in a 3.83% moisture content and for the fine aggregate, the formula resulted in a moisture content of 4.08%.

Table 15

Moisture analysis for both coarse and fine aggregate

Aggregate Type	Oven Dried (OD) mass (lbs)	Saturated Surface Dry (SSD) mass (lbs)	Percent Moisture
Coarse aggregate	3.13	3.25	3.83
Fine Aggregate	3.92	4.08	4.08

Water Analysis

Both the tap water and the wash water were tested for ph, total suspended solids, turbidity and total dissolved solids. The testing was not directly related to the research hypothesis. However, it was felt to be important to establish a baseline for future work.

The testing for pH followed ASTM D1293 (ASTM, 1999). An HACH Hq 40d pH meter was used for testing samples of both wash water from Central Concrete and tap water from the Mankato city water supply. Calibration of the meter was accomplished through automatic calibration using standard known solutions with a defined pH. Each sample of water was tested five times. The samples were placed in small beakers and the pH probe was placed in the water. The meter read the pH levels for the samples. Results are contained in Table 16. Test results for the tap water were consistent with the published test results for Mankato city water supply. Test results for the concrete wash water for Holcim Type 1 cement were consistent with pH levels listed in the MSDS. They showed slightly higher pH levels than published results from previous research by Parker and Slimak (1977) but did not change over time, as noted by Bhatty and Kozikowski (2004). The two studies each referenced pH levels for concrete wash water that were under 12. Interestingly, the pH levels using Central Concrete wash water had a lower standard deviation, meaning the test results were more uniform, than the results using the City of Mankato tap water.

Table 16

pH test results

Trial #	1	2	3	4	5	Mean	Standard Deviation (SD)
Tap	8.93	8.56	8.37	8.31	8.27	8.49	0.24
Wash water	12.46	12.49	12.50	12.48	12.49	12.48	0.01

n=5

Standards for the total suspended solids (TSS) are addressed in ASTM D3977 (ASTM, 1997). Samples of approximately 100 ml of both tap water and pond water samples were filtered and then decanted. The filtered material was dried in an oven overnight and then cooled in a dessicator, which prevented absorption of moisture as the material cooled. The dry material was weighed and compared to the original weight of the sample for a measure of total suspended solids, listed in milligrams per liter (mg/l). Table 17 lists the results of the TSS testing. The ASTM standard for suspended solids in the water used in a concrete mix calls for a maximum of 50,000 parts per million (PPM). PPM is calculated as milligrams per liter, so the results in Table 17 are both mg/l and PPM. The mean for suspended solids testing for the wash water from Central Concrete was approximately 240 PPM.

Table 17

Total Suspended Solids (TSS) measured in mg/l

Trial #	1	2	3	4	5	Mean	SD
Tap Water	.207	.407	.400	.820	.704	.508	.497
Wash Water	233.0	219.4	265.2	284.3	196.7	239.7	70.3

n=5

The total suspended solids, as expected, were significantly higher for the wash water samples. The data in graphical format are shown in Figure 15. Five trials produced a mean of .005 grams/liter for tap water and .239 grams per liter for wash water. The standard deviation of the five TSS samples of tap water was 4.97 and the standard deviation of the five TSS samples of wash water was 70.3.

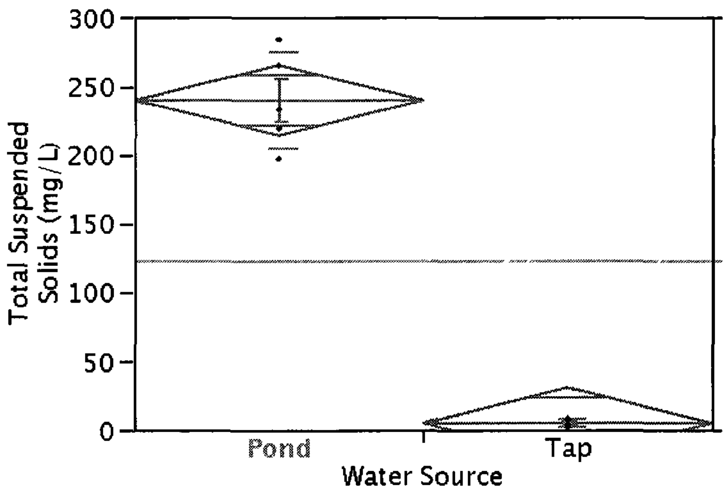

Figure 15. Total Suspended Solids by water source

Standards for the total dissolved solids (TDS) are also addressed in ASTM D3977 (ASTM, 1997). Five samples of both tap water and pond water, each approximately 10 ml, were weighed, filtered and then decanted. The filtered material was disposed. The remaining water was placed in a beaker and evaporated in an oven. The beaker was then cooled in a dessicator. After cooling overnight, the beaker was weighed and compared to the weight of the beaker before testing. The difference in weights was the amount of material that had been dissolved in the water. The amount of solid material remaining was then compared to the total volume of the water sample for a measure of Total Dissolved Solids. Table 18 lists the results of the TDS testing in mg/l.

Table 18

Total Dissolved Solids (TDS) measured in mg/l

Trial #	1	2	3	4	5	Mean	SD
Tap Water	111.1	010.0	014.0	067.7	0	40.6	131.1
Wash Water	2690.0	2774.1	2681.1	2749.0	2634.8	2705.9	111.5

n=5

The five trials of TDS testing for wash water produced a mean of 2705.9 mg/l of dissolved solids with a standard deviation of 111.5. The five trials of TDS testing for tap water produced a mean of 40.6 mg/l of dissolved solids with a standard deviation of 131.1. Results in boxplot format are shown in Figure 16.

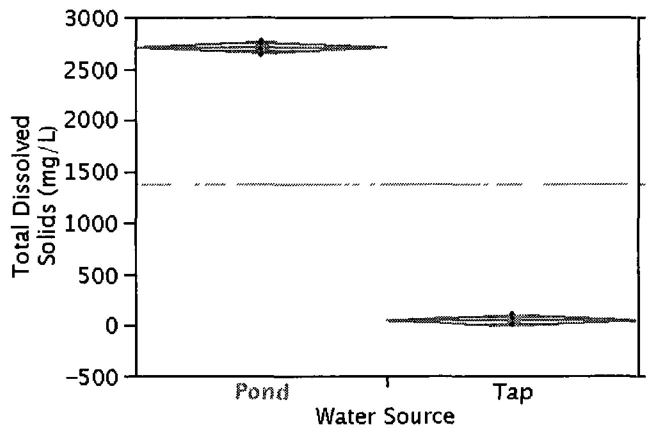

Figure 16. Total Dissolved Solids by water source

ASTM C6855 was used as a guide for testing the turbidity of both the tap water and the wash water (ASTM, 2010e). Turbidity, or the cloudiness of the water, is measured by the intensity of scattered light. The measured intensity is compared to a standard intensity for known liquids. Turbidity was measured using an Oakton T-100 Turbidimeter. Both the tap water and wash water were stirred before sampling. Table 19 contains the results of five trials each for tap water and wash water. The mean tap water measured 2.88 NTU compared to the mean wash water at 171 NTU. The standard deviation of the tap water was .31 while the standard deviation of the wash water was 13.91.

Table 19

Turbidity (NTU)

Trial #	1	2	3	4	5	Mean	SD
Tap water	2.81	2.93	2.91	3.35	2.39	2.88	.31
Wash water	165	182	154	162	192	171	13.91

n=5

Compressive Strength Analysis

After mixing the concrete samples, each batch was tested for slump in order to provide an advance indication of the final compressive strength of the concrete. The slump test was performed using methodology from ASTM C143 (ASTM, 2010f). The material used for the slump test was returned to the mix. Slump test results are listed in Table 20. The highest slump was 3 1/2" on batch AT-3 while the lowest slump was for batch AT-5 with a 1" slump. The slump for batch MT-4 was ¼" over the design limit. The other batches fell within the allowable design limits.

Table 20

Slump by batch

ACI Batches (Slump design 1-4")	Slump (in)	Mn/DOT Batches (Slump design 1-3")	Slump (in)
AT-1	2	MT-2	2
AT-3	3.5	MT-4	3.25
AT-5	1	MT-6	3
AP-2	1.5	MP-1	2
AP-4	2	MP-3	3
AP-6	2.75	MP-5	2

All cylinders were tested for compressive strength at 28 days, following procedures in ASTM C39 (ASTM, 2009e). The data for the individual cylinders is recorded in Appendix B. Data for the individual cylinders ranged from a high of 5795 psi for cylinder AP-6-1 to the lowest tested cylinder, MT-6-5, with a psi of 3500. Table 21 references measures of central tendency for the individual cylinder scores. The mean compressive strength of the 60 sample cylinders was 5047 psi, compared to the target compressive strength of 4000 psi. The standard deviation of the 60 samples was 575. With a standard deviation of 575, 68% of the samples fell between 4472 psi and 5622 psi, or one standard deviation from the mean and 95% of the samples fell between 3897 psi and 6197 psi, or two standard deviations from the mean.

Table 21

Measures of central tendency for individual cylinder samples

Number of Samples (N)	Mean (psi)	Median (psi)	Variance (s^2)	Standard Deviation (SD)
60	5047	5190	330948	575

Using the ACI formula (American Concrete Institute, 2007), for required average compressive strength, *f'cr = f'c* + 1.34s, the required average compressive strength for the samples was 4000 + 1.34(575) or 4770 psi. The mean compressive strength for the 60 samples was 5047 psi, which exceeded the ACI required average compressive strength.

NRMCA (2003) states that no concrete cylinder test results should be more than 500 psi lower than the target compressive strength and the average of any three tests should equal or exceed the target compressive strength. The data show that all 60 cylinders met the criteria. Only the MT-6-5 sample, at 3500 psi, had a marginal result, with a compressive strength at 500 psi lower than the target compressive strength of 4000 psi. In batch MT-6, results of all other cylinders in the batch were greater than the target compressive strength and the batch mean was 4226 psi, as shown in Table 22. The batch with the lowest mean compressive strength was MT-4, with a mean of 4045 psi, still above the target of 4000 psi. Since all cylinders were cast at the same time, the batch of five cylinders was considered as a unit and the average of all five is greater than the target compressive strength. Table 22 lists the compressive strength of the individual cylinders in MT-4, as well as the mean compressive strength for the batch.

Table 22

Mean compressive strength of batches MT-6 and MT-4

Batch Number	Sample					
	1	2	3	4	5	Mean
MT-6	4325	4395	4510	4400	3500	4226
MT-4	3960	3930	3890	4155	4290	4045

The compressive strength data, grouped by concrete batch and ranked from highest mean compressive strength to lowest mean compressive strength is listed in Table 23. The batch with the lowest mean compressive strength was batch 4 of the Mn/DOT mix using tap water (MT-4). The batch with the highest compressive strength was batch 6 of the ACI mix using wash water (AP-6). Batch MT-4 contained three cylinders slightly below the target 4000 psi. However, the remaining two cylinders were higher than the target compressive strength and the mean for the batch was 4045 psi, still above the target. Of note is that batch MT-4, with slump .25 inches greater than design criteria, had the lowest mean compressive strength. Batch MT-6 contained the outlier sample. However, the four other samples were substantially above the target compressive strength and the batch mean was 4226 psi.

Batch AP-6 not only had the highest mean compressive strength, but also had the lowest variability, as indicated by a standard deviation of 77.1. The standard deviations of the ACI batches ranged from 77.1 for batch AP-6 to 201.7 for batch AT-5. For the

Mn/DOT batches, variability was higher, with a range of standard deviations from 152.4 for batch MT-4 to 367.8 for batch MT-6.

Table 23

Data grouped by batch, ranked from highest to lowest compressive strength

Batch ID	Compressive Strength (psi) Mean	High	Low	Range	Standard Deviation (SD)
AP-6	5732	5795	5580	215	77.1
AP-4	5599	5735	5440	295	111.6
AT-1	5541	5745	5395	350	157.3
AT-5	5483	5680	5105	575	201.7
AP-2	5464	5750	5295	455	162.7
AT-3	5370	5605	5285	320	120.3
MP-5	4939	5200	4525	675	256.1
MP-1	4833	5145	4500	645	204.9
MP-3	4672	4970	4485	485	172.8
MT-2	4656	4840	4300	540	187.9
MT-6	4226	4510	3500	1010	367.8
MT-4	4045	4290	3890	400	152.7

n=5

Figure 17 represents the compressive strength data for each batch of concrete in graphical format using a boxplot. The compressive strength for each sample of each batch is represented by a small dot. The box for each batch shows a horizontal line representing the median score for that batch. The top and bottom of each box is represented by the interquartile range for that batch. With five scores for each batch, the interquartile range is represented by the second highest and second lowest scores. The width of the diamond is a function of the number of trials represented in each batch.

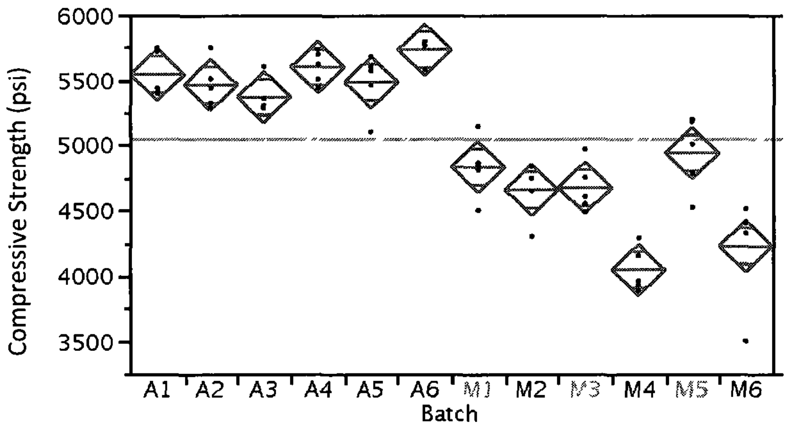

Figure 17. Boxplot for each concrete batch

When grouped by mix design, the data clearly show that the ACI mix had a higher compressive strength than the Mn/DOT mix. The mean compressive strength of the ACI mix was 5531 psi and the mean compressive strength of the Mn/DOT mix was 4561 psi, a difference of 970 psi, or 17.5%. The range and standard deviation of the Mn/DOT mix was also significantly higher than the ACI mix. Table 24 represents the compressive strength by mix design data.

Table 24

Compressive strength by concrete mix design

Mix Design	Mean compressive strength (psi)	Highest compressive strength (psi)	Lowest compressive strength (psi)	Range	Standard Deviation (SD)
ACI mix	5531	5795	5105	690	144.2
Mn/DOT mix	4561	5200	3500	1700	235.0

n=30

Figure 18 represents the compressive strength data grouped by concrete mix design in a graphical format. The graph shows the interquartile range and median for each mix.

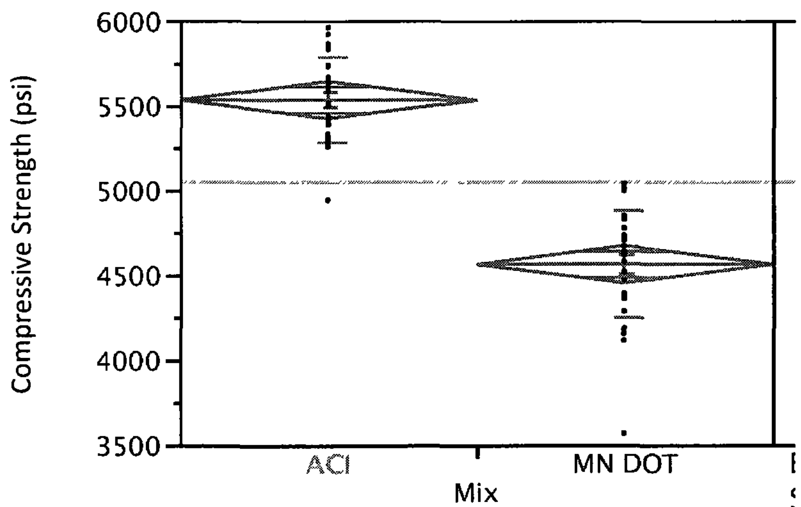

Figure 18. Compressive strength by mix design

The data were then grouped by water source. The mean compressive strength of the wash water samples was 321 psi higher than the mean compressive strength of the tap water samples. The variability of the tap water samples, represented by a standard deviation of 213.6, was greater than the variability of the wash water samples, with a standard deviation of 174.3. Table 25 represents the data grouped by water source.

Table 25

Compressive strength by water source

Water Source	Mean compressive strength (psi)	Highest compressive strength (psi)	Lowest compressive strength (psi)	Range	Standard Deviation (SD)
Tap water	4886	5745	3500	2180	213.6
Wash Water	5207	5795	4485	1315	174.3

n=30

Figure 19 represents the compressive strength data grouped by water source in graphical format. The veritical lines in the graph represent the range of compressive strengths for the two sets of samples.

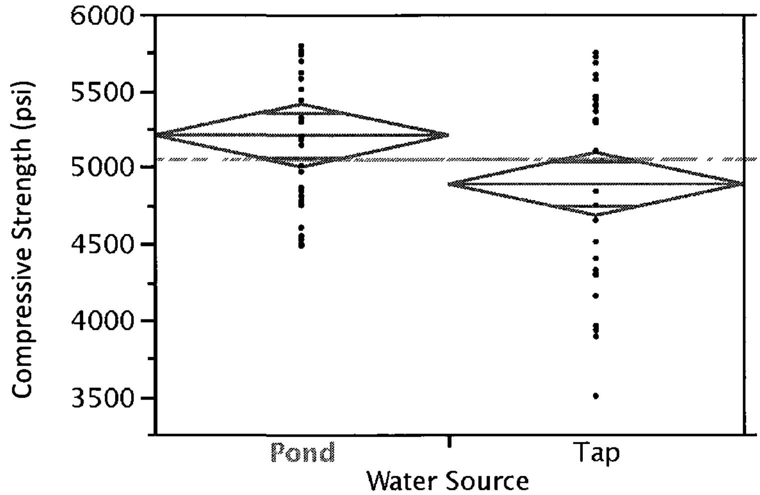

Figure 19. Compressive strength by water source

Two-Way ANOVA

The compressive strength data were then grouped by both the mix design and water type. The results are shown in Table 26. The highest compressive strength for a sample using the ACI mix with tap water was 5745 psi and the highest compressive strength of a sample using the ACI mix with wash water with was 5795, a difference of 50 psi, less than one percent. Both ACI mixes had lower ranges of scores and lower standard deviations compared to the Mn/DOT mixes. The Mn/DOT tap water had a range of scores from 3500 psi to 4840 psi, a range of 1340 psi. The outlier, MT-6-1 was 390 psi less than the next lowest Mn/DOT tap water sample. The Mn/DOT wash water samples had a range of 715 psi. The Mn/DOT wash water samples also had a higher mean compressive strength and a higher maximum compressive strength than the Mn/DOT tap water samples.

Table 26

Compressive strength by concrete mix design and water source

Mix Design	Water Type	Mean compressive strength (psi)	Highest compressive strength (psi)	Lowest compressive strength (psi)	Range	Standard Deviation (SD)
ACI	Tap	5465	5745	5395	350	163.2
ACI	Wash	5598	5795	5295	500	122.3
Mn/DOT	Tap	4309	4840	3500	1340	254.2
Mn/DOT	Wash	4815	5200	4485	715	214.0

n=15

Figure 20 represents the same data using a boxplot. The variability of the Mn/DOT mixes is evident by the dots that are outside the interquartile ranges. The two Mn/DOT mixes are lower in compressive strength than the two ACI mixes. The Mn/DOT tap water mix is also lower in compressive strength than the Mn/DOT wash water mix and both Mn/DOT mixes are lower in strength than either ACI mix.

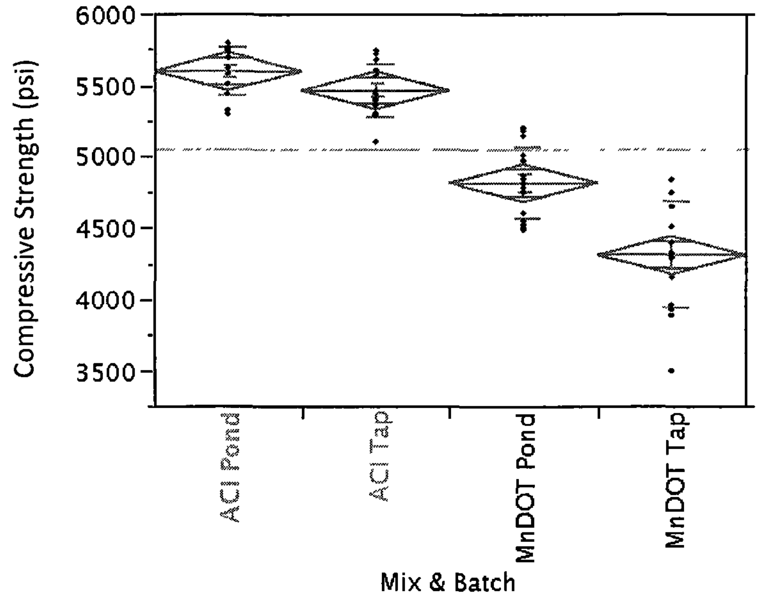

Figure 20. Boxplot of ACI and Mn/DOT mixes by water source

The relationships between the variables were then analyzed using the two-way ANOVA method. The dependent variable was the mean compressive strength of the cylinders and the two independent variables were water source and mix type. There were two levels to the water source variable, wash water and tap water. There were also two levels to the mix type variable, ACI and Mn/DOT. Table 27 contains the means and marginal means of the two-way ANOVA groups. The marginal mean across water sources shows a difference of 320 psi, a difference of approximately 5%. The marginal mean across mix types was 970, a difference of 17%.

Table 27

Two-way ANOVA means and marginal means

Mix Design	Tap water (psi)	Wash water (psi)	Marginal Mean Mix Design (psi)
ACI	5465	5598	5532
Mn/DOT	4309	4815	4562
Marginal Mean Water Source	4887	5207	

n=30

For the two-way ANOVA, three effects were tested. The first main effect tested was water source collapsed across mix design. The second main effect tested was mix design collapsed across water source. The final effect tested was the interaction of water source and mix design.

The sum of the squares was calculated for each of the effects, as well as the variability within the groups. The results were divided by the degrees of freedom to calculate the mean square. The critical value for F with 1 and 56 degrees of freedom is approximately 4.02. The mean square from the main effect of water source was then divided by the mean square within to compute the F value. The F (1, 56) value was calculated to be 19.29 and is significant for α=.05. The main effect of mix design had an F (1, 56) value of 191.93, which was significant for α=.05. The F (1, 56) value for the interaction of water source and mix design was 5.98, which also was significant at α=.05. The results of the two-way ANOVA are shown in Table 28.

Table 28

Two-way ANOVA

	Sum of Squares	Degrees of Freedom	Mean Square	*F*	Sig
Main effect Water source	1365042	1	1365042	19.29	.000
Main effect Mix Design	13585041	1	13585041	191.93	.000
Water*Mix	423360	1	423360	5.98	.018
Within	3963780	56	70782		
Total	19337223	59			

The strength of relationship was calculated using eta^2 for each effect. Table 29 contains the results of computations for eta^2, showing the main effect of mix design had 70% of the total variability.

Table 29

Eta^2

Effect	Eta^2
Main effect water source	.07
Main effect mix design	.70
Water source*mix design	.02

Tukey's Honestly Significant Difference (HSD) was used to determine if the results showed a critical difference (CD). Table 30 contains the results of the Tukey's HSD analysis. Compressive strength test results from each of the four groups, AT, AP, MT and MP were compared to each of the other groups. The ACI mix with tap water and Mn/DOT mix with tap water groups did not show a significant difference at $\alpha=.05$. However, all of the other combinations showed a significant difference, as represented by the .000 value in the significance.

Table 30

Tukey's HSD

Mix & Water	Mix & Water	Mean Difference	Standard Error	Significance
ACI Tap	ACI Wash	783.667	93.876	.000
	Mn/DOT Tap	133.667	93.876	.490
	Mn/DOT Wash	1289.333	93.876	.000
ACI Wash	ACI Tap	-783.667	93.876	.000
	Mn/DOT Tap	-650.000	93.876	.000
	Mn/DOT Wash	505.667	93.876	.000
Mn/DOT Tap	ACI Tap	-133.667	93.876	.490
	ACI Wash	650.000	93.876	.000
	Mn/DOT Wash	1155.667	93.876	.000
Mn/DOT Wash	ACI Tap	-1289.333	93.876	.000
	ACI Wash	-505.667	93.876	.000
	Mn/DOT Tap	-1155.667	93.876	.000

CHAPTER V

CONCLUSIONS, RECOMMENDATIONS AND SUMMARY

This study was designed to be a first step in a series of applied research projects to test the usability of recycling concrete wash water back into the concrete mix. The EPA and MPCA have created regulations that have forced a change to the traditional method of washing off ready mix delivery trucks, washing truck chutes and washing tools used in the finishing of concrete. The regulations have cost many ready mix companies upwards of $50,000 to remodel wash out pits and an additional $1600 per truck to outfit them with wash water return systems. The current BMPs do not include reuse of the wash water, resulting in a conundrum. If the water can't be dumped at the job site and must be returned to the ready mix plant, where does it go then? If there is too much water at the ready mix plant, what can be done with it? The answers are less than stellar methods for dealing with the excess water, including dumping in a quarry, dumping in a wetland and dumping in a river. The environmentally responsible thing to do is find a way to recycle the water.

A number of wash water factors were investigated in order to develop a baseline for future work. The pH of both the city water and the wash water were tested. The wash water from Central Concrete had higher pH levels than either Parker and Slimak (1977) or Bhatty and Kozikowski (2004). The reason for the high pH levels was beyond the scope of this study. However, the effects of pH on compressive strength may be an excellent investigation in the future. The wash water was taken from the surface of the settlement pond at the ready mix plant and a high percentage of the suspended solids had a chance to settle out of the water. This was a different approach from previous research which used water immediately after mixing concrete. There was no timeframe required for reintroducing into the mix, as was noted in the Borger (1993) work. The reasoning behind the choice of wash water from the settlement pond in the mix is that, if regulations change, the settlement pond will be the most likely place to collect the water for reuse. The dissolved solids were tested for the amount of dissolved solids, but chemical analysis was beyond the scope of this study. The wash water from concrete mixes that use admixtures and fly ash would likely have some chemical residue remaining in the wash water. A future investigation could analyze the water for chemical compounds that could make reuse of the water highly undesirable. There would need to be special attention paid to salts, which would shorten the usable lifespan of the concrete. Finally, suspended solids were analyzed in the water samples. For this research, the wash water was scooped from the top of the settlement pond in order to eliminate one source of variability in the mixes. Manipulating the amount of suspended material so it was near the 50,000 ppm allowed by ASTM was beyond the scope of this study, but would be a challenging and informative future project. Past research, including Borger (1993) used wash water with varying levels of suspended solids.

Other interesting results were observed during this experiment, though not directly related to the hypothesis. The slump of a concrete batch is determined by time of mixing, the water content of the aggregates and the water to cement ratio used in the mix design. The time of mixing was carefully observed. The water content in each batch varied slightly, due to the ever changing moisture content of the aggregates and the practice of the operator to reserve a small amount of water in order to ensure the slump of the batch matched the design criteria. In this study, the expected inverse relationship between slump and compressive strength was inconsistent. The slump of batch MT-4 was the highest compared to the design criteria and the batch had the lowest mean compressive strength, as expected. The slump of batch AT-3 was the highest of all batches, but the compressive strength was at the median point when compared to all other batches of concrete. Batch AT-5 had the lowest slump of the three AT batches and had the median compressive strength of the three batches. The results are not consistent with what is a generally accepted idea in the industry.

Compressive strength and fracture types also do not appear to be related. Sample AP6-5 had the highest compressive strength of all samples and had fracture type 3. Sample MT6-5 had the lowest compressive strength of all samples and also had fracture type 3. The sample with the highest compressive strength and the sample with the lowest compressive strength both had the same fracture type. Fracture type 5 was, as stated in ASTM 39, prevalent with the unbonded caps used in this study. Future work could be more reliable with the used of bonded caps, rather than the unbonded.

At the outset of this study, it was anticipated that concrete made with wash water from a settlement pond, with a TSS level less than 50,000 PPM, and concrete made with tap water might have a similar compressive strength. This study has demonstrated that, under limited conditions, there is a significant difference between the compressive strength of concrete made using wash water and that of concrete made using tap water. The research showed that the Mn/DOT mix, containing fly ash, water reducer and air entrainment admixtures, had a higher degree of variability across both wash water and tap water than the ACI mix, which contained no admixtures. The two-way ANOVA showed an *F* value of 19.29 when the main effect of water source was collapsed across mix design and an *F* value of 191.93 when the main effect of mix design was collapsed across water source. The *F* value for the interaction of water and mix was 5.98. The strength of relationship using eta^2 showed that the mix design was responsible for 70% of the total variability. When the four groups of cylinders, ACI mix with tap water, ACI mix with wash water, Mn/DOT mix with tap water and Mn/DOT mix with wash water were compared using Tukey's HSD, the water source, wash water and tap water, showed a statistically significant difference.

Across all test groups, the concrete made with wash water had a compressive strength that was significantly higher than concrete made with tap water. The research data demonstrated that the null hypothesis should be rejected and that there is a statistically significant difference between using tap water in a concrete mix and using wash water in a concrete mix.

Recommendations for Further Study

The variability of using 12 small batches was challenging for consistency of results in this study. The margin of error for admixtures and water was very small. Slump changed by 2" with the addition of a few ounces of water. Larger batches would mitigate some of the variability, such as found with the sample MT-6-5, with a compressive strength 825 psi lower than any other sample in the batch. A follow up study using only one concrete mix design and multiple sources of wash water would be an excellent next step in the study of the reuse of wash water. Since most concrete mixes use fly ash, water reducers and air entrainment, it would make sense to use a mix with all three compounds, similar to the Mn/DOT mix. Further study of the use of concrete wash water would be recommended by field testing using a test slab such as a driveway. Testing samples from batches containing 5-10 yards of concrete would contribute to the body of knowledge and extend the information provided by this limited study.

In addition to compressive tests of cylinders, other concrete tests would help to establish criteria for reuse of wash water. The suggested concrete slabs would need to be exposed to the freeze/thaw cycle and then be tested for durability. Concrete beams could be cast which could then be tested for flexural strength. Different reinforcements could be introduced in order to study any potential effects on iron in the rebar.

Summary

The reuse of concrete wash water would be of benefit to the ready mix companies, the contractors and the environment. The ready mix companies unanimously supported the research. The owners of the ready mix companies that were included in the study had concerns about the costs of meeting the new regulations. There are additional costs associated with each delivery and additional costs for capital improvements needed to meet the new guidelines. With costs and profitability in mind, they were interested in research which showed a best management practice for dealing with the new regulations requiring the control of wash water. The contractors were interested in a method of saving both time and money associated with the control of concrete wash water. The environmental benefit would include reuse of a material previously classified as waste.

This study has been an excellent introduction to the quantitative research methods of Industrial Technology. In spite of the quantitative nature of the research, the author has been privileged to interview numerous people expressing multiple views on this topic. The passion of environmentalists, the business savvy of the ready mix owners and the practical nature of the contractors have been viewed, reviewed and considered in the writing of this study. This quantitative research may be an excellent starting place for further research, but both change of public policy and change of traditional methods will require more than quantitative proof of the efficacy of reuse of concrete wash water. It will require the building of positive relationships among divergent groups, including owners, contractors, inspectors and ready mix suppliers.

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APPENDIX A

DEFINITIONS OF COMMON TERMS

Accelerating admixture--"admixture that speeds the rate of hydration of hydraulic cement, shortens the normal time of setting, or increases the rate of hardening, of strength development, or both, of portland cement, concrete, mortar , grout, or plaster" (Kosmatka, Kerkhoff, & Panarese, 2005, p. 335).

Admixture--"a material other than water, aggregates, hydraulic cementitious material, and fiber reinforcement that is used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing" (ASTM, 2010d, p. 2).

Aggregate--"Aggregate is sand, gravel and crushed stone in their natural or processed state. In Minnesota, aggregate companies mine glacial sand and gravel deposits and quarry limestone, quartzite, granite and other igneous rock formations" (Aggregate Ready Mix of Minnesota, 2010).

Air entrainment--"intentional introduction of air in the form of minute, disconnected bubbles (generally smaller than 1 mm) during mixing of portland cement concrete, mortar, grout, or plaster to improve desirable characteristics such as cohesion, workability, and durability" (Kosmatka et al., 2005, p. 335).

Axial load--"a load that is applied parallel to the cylindrical axis of the member" (Axial Load, 2010).

Batching--"process of weighing or volumetrically measuring and introducing into the mixer the ingredients for a batch of concrete, mortar, grout, or plaster" (Kosmatka et al., 2005, p. 335).

Best Management Practice (BMP)--"a vague term, broadly used to describe the most effective, feasible method that does the job. In the context of storm water management, it is often used to mean a structure or technology used to manage or treat the water such as a hooded catch basin, detention basin, or a filter system" (Massachusettes Department of Environmental Protection, 2010).

Binder--"material forming the matrix of concretes, mortars, and sanded grouts" (ACI Concrete Terminology, 2010, p. CT-6).

Blast-furnace slag--a by-product of steel making used to replace a portion of the cement in a concrete mix. "The nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace" (ASTM, 2010d, p. 3).

Calcium silicate hydrate--the most important cementing component of concrete. "contains lime (CaO) and silicate (SiO_2) in a ratio on the order of 3 to 2" (Kosmatka et al., 2005, p. 5).

Cementitious material (hydraulic)--"an inorganic material or a mixture of inorganic materials that sets and develops strength by chemical reaction with water by formation of hydrates" (ASTM, 2010d, p. 3).

Clinker--"a partially fused product of a kiln, which is ground to make cement" (ACI Concrete Terminology, 2010, p. CT-11).

Coarse aggregate--"aggregate that is predominantly retained on the No. 4 (4.75 mm) sieve" (ASTM, 2010d, p. 2).

Compaction--"process of inducing a closer arrangement of the solid particles in freshly mixed and placed concrete, mortar, or grout by reduction of voids, usually by vibration, tamping, rodding, puddling, or a combination of these techniques. Also called consolidation" (Kosmatka et al., 2005, p. 336).

Compressive strength--"maximum resistance that a concrete, mortar, or grout specimen will sustain when loaded axially in compression in a testing machine at a specified rate; usually expressed as force per unit of cross sectional area, such as megapascals (MPa) or pounds per square inch (psi)" (Kosmatka et al., 2005, p. 336)

Concrete--"Concrete is a mixture of two components: aggregates and paste. The paste, comprised of cement and water, binds the aggregates (usually sand and gravel or crushed stone) into a rocklike mass as the paste hardens because of the chemical reaction of the cement and water. Supplementary cementitious materials and chemical admixtures may also be included in the paste" (Concrete Technology, 2010a).

Concrete-chute rinse-off water (wash water)--"liquid wastes generated when a ready mix truck operator washes non-structural concrete materials off the chutes used to deliver concrete to a project" (Concrete Washout Guidance, 2009, p.2)

Concrete mix design--"the process of determining required and specifiable characteristics of a concrete mixture" (Kosmatka et al., 2005, p. 149).

Desiccant--"A substance used to withdraw moisture from other materials. Although the removal of large quantities of water is done by evaporation, aided by moving air currents and by elevated temperature, the last traces of moisture are often held very tightly and do not evaporate readily. Furthermore, evaporation ceases when the moisture content of the material is reduced to that of the drying-air current. For final drying, a desiccant is used. This is a substance with a high affinity for water, that is, it is hygroscopic" (Hanson & Marshall, 2008).

f'c--"specified compressive strength, psi" (American Concrete Institute, 2007, p. 14).

f'cr--"required average compressive strength, psi" (American Concrete Institute, 2007, p. 14).

Fine aggregate--"aggregate passing the 9.5mm (3/8-in.) sieve and almost entirely passing the 4.75mm (no.4) sieve and predominantly retained on the 75μm (No. 200) sieve" (ASTM, 2010d, p.4).

Fines--material finer than the No. 200 sieve. "The extremely fine material (clay, silt, dust or loam) occurring in most aggregates" (American Concrete Institute, 2007, p. 27).

Fineness modulus (FM)--specified sieves are No. 4, 8, 16, 30, 50, 100 sieves. "factor obtained by adding the cumulative percentages of material in a sample of aggregate retained on each of a specified series of sieves and dividing the sum by 100 (Kosmatka et al., 2005, p. 337).

Flush water--"water carried on a truck mixer in a special tank for flushing the interior of the mixer after discharge of the concrete" (ACI Concrete Terminology, 2010, p. CT-60).

Fly ash--a by-product of coal fired power plants used to replace a portion of the cement in a concrete mix. "The finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system" (ASTM, 2010d, p. 4).

Grading--"size distribution of aggregate particles, determined by separation with standard screen sieves" (Kosmatka et al., 2005, p. 337).

Hydration--"in concrete, mortar, grout, and plaster, the chemical reaction between hydraulic cement and water in which new compounds with strength-producing properties are formed" (Kosmatka et al., 2005, p. 33).

Hydraulic cement--"cement that sets and hardens by chemical reaction with water, and is capable of doing so under water" (Kosmatka et al., 2005, p. 3).

Lift--"the concrete placed between two consecutive horizontal construction joints, usually consisting of several layers or courses" (ACI Concrete Terminology, 2010, p. 40).

Material Safety Data Sheet (MSDS)--a form with data regarding the properties of a substance. "MSDS sheets are a widely used system for cataloging information on chemicals, chemical compounds, and chemical mixtures. MSDS information may include instructions for the safe use and potential hazards associated with a particular material or product" (Material safety data sheet, 2010).

Neat portland cement paste--material used to cap a concrete test cylinder. "A plastic mixture of hydraulic cement and water both before and after setting and hardening" (ACI Concrete Terminology, 2010, p. 13).

Oven dry--“completely dry and fully absorbent” (American Concrete Institute, 2007, p. 29).

pH--“a measure of the hydrogen-ion concentration on a log scale” (Kosmatka et al., 2005, p. 76).

Plastic concrete--“is that freshly mixed structural concrete which is pliable and capable of being molded or shaped like a lump of modeling clay” (Concrete Washout Guidance, 2009, p. 2).

Portland cement--“calcium silicate hydraulic cement produced by pulverizing portland cement clinker, and usually containing calcium sulfate and other compounds” (Kosmatka et al., 2005, p. 339)

Pozzolan--“siliceous or siliceous and aluminous materials, like fly ash or silica fume, which in itself possess little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (Kosmatka et al., 2005, p. 339).

Saturated and surface dry (SSD)--“ideal condition in which the aggregate neither contributes water to nor absorbs water from the paste” (American Concrete Institute, 2007, p. 28).

Sediment--“the material that settles to the bottom of a liquid” (American Heritage Dictionary, 1991, p. 1109).

Settlement pond--"larger than a catchment basin and preferably with lower velocity waterflows that enable suspended sediment to settle before the flow is discharged into a creek" (Settlement pond glossary, 2010).

Sieve--"a device with meshes or perforations through which finer particles of a mixture (as ashes, flour, or sand) may be passed to separate them from coarser ones" (Merriam-Webster Dictionary, 2010).

Slump--"a measure of consistency of freshly mixed concrete measured to the nearest 1/4 inch immediately after removal of the slump cone mold" (Nolan, 2000, p.289)

Slurry--"a liquid mixture of cement or other finely divided material and water" (Taylor, 1965, p. 621).

Specific gravity--"the ratio of the weight of a given solid volume of material to the weight of an equal volume of water" (American Concrete Institute, 2007, p. 30).

Storm Water Pollution Prevention Plans (SWPPP)--"the plan to control sediment laden runoff and erosion prevention from the beginning of the project to the end and may include post construction measures" (Storm water pollution prevention plan requirements, 2009, p. 1)

Strikeoff--"the process of cutting off excess concrete to bring the top surface of a slab to proper grade" (Kosmatka et al., 2005 p. 200).

Tamping--"the operation of compacting freshly placed concrete by repeated blows" (Taylor, 1965, p. 622).

Tensile strength--"the maximum stress that a material is able to resist under axial tensile loading, before failing" (Nolan, 2000, p. 289).

Total dissolved solids (TDS)--solids that pass through a 2 micron filter. "TDS comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulfates) and some small amounts of organic matter that are dissolved in water" (Water-research, 2010).

Total suspended solids (TSS)--solids that are too large to pass through a 2 micron filter. TSS are "solid materials, including organic and inorganic, that are suspended in the water. These would include silt, plankton and industrial wastes" (North Dakota Department of Health surface water, 2010).

Turbidity--"having sediment or foreign particles stirred up or suspended; muddy" (American Heritage Dictionary, 1991, p. 1304).

Water reducing admixture--" an admixture that either increases slump of freshly mixed mortar or concrete without increasing water content or maintains slump with a reduced amount of water, the effect being due to factors other than air entrainment" (ACI Concrete Terminology, 2010, p. CT-10).

Water to cementing (cementitious) material ratio--w/c "ratio of the mass of water to mass of cementing materials in concrete, including portland cement, blended cement, hydraulic cement, slag, fly ash, silica fume, calcined clay, metakoaolin, calcined shale, and rice husk ash" (Kosmatka, et al., 2005, p. 340).

Weir system--"a small, overflow type dam commonly used to raise the level of a river or stream. Weirs have traditionally been used to create mill ponds" (Weir, 2010).

Workability--"that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition" (ACI Concrete Terminology, 2010, p. CT-61).

APPENDIX B

COMPRESSIVE STRENGTH OF CYLINDERS

ACI Mix with Tap water

	Cylinder code	**Water Type**	**Compressive Strength @ 28 Days (psi)**	**Mean/ Batch**	**Variance (s^2)**	**Standard Deviation (SD)**
Batch 1						
	AT-1-1	Tap Water	5405			
	AT-1-2	Tap Water	5720			
	AT-1-3	Tap Water	5395			
	AT-1-4	Tap Water	5440			
	AT-1-5	Tap Water	5745			
Totals Batch 1			27705	5541	24734	157.3
Batch 3						
	AT-3-1	Tap Water	5305			
	AT-3-2	Tap Water	5285			
	AT-3-3	Tap Water	5605			
	AT-3-4	Tap Water	5295			
	AT-3-5	Tap Water	5360			
Totals Batch 3			26850	5370	14480	120.3
Batch 5						
	AT-5-1	Tap Water	5620			
	AT-5-2	Tap Water	5505			
	AT-5-3	Tap Water	5735			
	AT-5-4	Tap Water	5695			
	AT-5-5	Tap Water	5440			
Totals Batch 5			27415	5483	40696	201.7

ACI Mix with Wash Water

	Cylinder code	**Water Type**	**Compressive Strength @ 28 Days (psi)**	**Mean/ Batch**	**Variance (s^2)**	**Standard Deviation (SD)**
Batch 2						
	AP-2-1	Wash Water	5750			
	AP-2-2	Wash Water	5295			
	AP-2-3	Wash Water	5510			
	AP-2-4	Wash Water	5440			
	AP-2-5	Wash Water	5325			
Totals Batch 2			27320	5464	26474	162.7
Batch 4						
	AP-4-1	Wash Water	5620			
	AP-4-2	Wash Water	5505			
	AP-4-3	Wash Water	5735			
	AP-4-4	Wash Water	5695			
	AP-4-5	Wash Water	5440			
Totals Batch 4			27995	5599	12454	111.6
Batch 6						
	AP-6-1	Wash Water	5795			
	AP-6-2	Wash Water	5760			
	AP-6-3	Wash Water	5760			
	AP-6-4	Wash Water	5580			
	AP-6-5	Wash Water	5765			
Totals Batch 6			28660	5732	5946	77.1

Mn/DOT Mix with Tap Water

	Cylinder code	**Water Type**	**Compressive Strength @ 28 Days (psi)**	**Mean/ Batch**	**Variance (s2)**	**Standard Deviation (SD)**
Batch 2						
	MT-2-1	Tap Water	4745			
	MT-2-2	Tap Water	4650			
	MT-2-3	Tap Water	4840			
	MT-2-4	Tap Water	4745			
	MT-2-5	Tap Water	4300			
Totals Batch 2			23280	4656	35294	187.9
Batch 4						
	MT-4-1	Tap Water	3960			
	MT-4-2	Tap Water	3930			
	MT-4-3	Tap Water	3890			
	MT-4-4	Tap Water	4155			
	MT-4-5	Tap Water	4290			
Totals Batch 4			20225	4045	23320	152.7
Batch 6						
	MT-6-1	Tap Water	4325			
	MT-6-2	Tap Water	4395			
	MT-6-3	Tap Water	4510			
	MT-6-4	Tap Water	4400			
	MT-6-5	Tap Water	3500			
Totals Batch 6			21130	4226	135274	367.8

Mn/DOT Mix with Wash Water

	Cylinder code	Water Type	Compressive Strength @ 28 Days (psi)	Mean/ Batch	Variance (s^2)	Standard Deviation (SD)
Batch 1						
	MP-1-1	Wash Water	4865			
	MP-1-2	Wash Water	4845			
	MP-1-3	Wash Water	4500			
	MP-1-4	Wash Water	5145			
	MP-1-5	Wash Water	4810			
Totals Batch 1			24165	4833	41986	204.9
Batch 3						
	MP-3-1	Wash Water	4970			
	MP-3-2	Wash Water	4550			
	MP-3-3	Wash Water	4485			
	MP-3-4	Wash Water	4605			
	MP-3-5	Wash Water	4750			
Totals Batch 3			23360	4672	29846	172.8
Batch 5						
	MP-5-1	Wash Water	5200			
	MP-5-2	Wash Water	4780			
	MP-5-3	Wash Water	5010			
	MP-5-4	Wash Water	4525			
	MP-5-5	Wash Water	5180			
Totals Batch 5			24695	4939	65584	256.1

APPENDIX C

FRACTURE TYPES

MT-6-5 Type 3 Fracture

AT-3-2-Type 5 Fracture

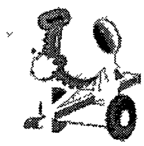
MP-5-1 Type 2 Fracture

MT-2-2 Type 1 Fracture

APPENDIX D

CONCRETE MIX DESIGNS

ACI Mix Design



Concrete Mix Design
Absolute Volume Method
US Units

Non-Air-Entrained

1) SLUMP

Recommended slumps for various types of construction		
Types of construction	**Maximum Slump (in.)**	**Minimum Slump (in.)**
Reinforced foundation walls and footings	3	1
Plain footings, caissons, and substructure walls	3	1
Beams and reinforced walls	4	1
Building columns	4	1
Pavements and slabs	3	1
Mass concrete	2	1

Enter (from Table above) slump values

maximum = 4 in

minimum = 1 in

Next Step

Start of Computations

2) MAXIMUM AGGREGATE SIZE

Enter the nominal maximum size of coarse aggregate = 3/4 in

Next Step

Previous Step

Start of Computations

3) MIXING WATER & AIR CONTENT

NON-AIR-ENTRAINED CONCRETE								
Amount of mixing water (lb/yd³) for indicated nominal maximum sizes of aggregate								
Slump (in.)	**3/8 in.**	**1/2 in.**	**3/4 in.**	**1 in.**	**1 1/2 in.**	**2 in.**	**3 in.**	**6 in.**
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	-
More than 7	-	-	-	-	-	-	-	-
Approximate amount of entrapped air in non-air-entrained concrete (%)								
Slump (in.)	**3/8 in.**	**1/2 in.**	**3/4 in.**	**1 in.**	**1 1/2 in.**	**2 in.**	**3 in.**	**6 in.**
All	3 0	2 5	2 0	1 5	1 0	0 5	0 3	0 2

Enter (from Table above) water weight for non-air-entrained concrete = 340 lb/yd^3

Enter (from Table above) amount of entrapped air = 2 %

[Compute]

Volume of water = 5 449 ft^3

Volume of air = 0 54 ft^3

Next Step   Previous Step   Start of Computations

4) WATER-CEMENT RATIO

Relationship between water-cement or water-cementitious materials ratio and compressive strength of concrete	
Compressive strength at 28 days (psi)	**Water-cement ratio by weight (Non-air-entrained concrete)**
6000	0 41
5000	0 48
4000	0 57
3000	0 68
2000	0 82

Enter compressive strength at 28 days = 4000 psi

Enter (from Table above) water-cement (or water-cementitious materials) ratio = 57

Important! Check the maximum permissible water-cement ratio from the Table below and revise the water-cement ratio entered in the box above accordingly.

Maximum permissible water-cement or water-cementitious materials ratios for concrete in severe exposure		
Type of Structure	**Structure wet continuously and exposed to frequent freezing and thawing**	**Structure exposed to sea water or sulfates**
Thin section (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 in. cover over steel	0.45	0.40
All other structures	0.50	0.45

Enter the specific gravity of the cement (if unknown, use 3.15) = 3 15

Compute

Weight of cement = 596 491 lb/yd^3

Solid volume of cement = 3 035 ft^3

Are pozzolanic materials [such as Fly Ash, Silica Fumes, Ground Granulated Blast-Furnace Slag (GGBFS)] used in the mix?

* NO, click here to proceed with regular mix design.

* YES, select desired calculation method, and make input in one of the Tables below:

Weight Equivalency Method	Volume Equivalency Method
If pozzolanic materials percentage by weight of cementitious material is known, click here ◯, and **Enter** this percentage %	If pozzolanic materials percentage by weight of cementitious material is known, click here ◯, and **Enter** this percentage %
If pozzolanic materials percentage by volume of cementitious material is known, click here ◯, and **Enter** this percentage %	If pozzolanic materials percentage by volume of cementitious material is known, click here ◯, and **Enter** this percentage %

Enter specific gravity of pozzolanic material (if unknown, use 2.4) =

Compute

Adjusted water-cementitious materials ratio (only for volume equivalency method) =

Weight of pozzolanic materials = lb/yd^3

Weight of cement = lb/yd^3

Solid volume of cement plus pozzolanic materials = ft^3.

Next Step | Previous Step | Start of Computations

5) COARSE AGGREGATE

Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate				
Nominal maximum size of aggregate (in.)	**2.40**	**2.60**	**2.80**	**3.00**
3/8	0 50	0 48	0 46	0 44
1/2	0 59	0 57	0 55	0 53
3/4	0 66	0 64	0 62	0 60
1	0 71	0 69	0 67	0 65
1 1/2	0 75	0 73	0 71	0 69
2	0 78	0 76	0 74	0 72
3	0 82	0 80	0 78	0 76
6	0 87	0 85	0 83	0 81

Display Nominal maximum size of aggregate = 3/4 in

Enter unit weight of coarse aggregate (if unknown, use 95 to 120 lb/ft^3 for normal weight aggregate) = 95 lb/ft^3

Enter fineness modulus of fine aggregate = 2 75

Enter (from Table above) volume of coarse aggregate per unit volume of concrete = 62

Enter specific gravity of coarse aggregate (if unknown, use 2 55 to 2 75 for normal weight aggregate) = 2 55

Compute

Weight of coarse aggregate = 1590 3 lb/yd^3

Solid volume of coarse aggregate = 9 994 ft^3

Next Step | Previous Step | Start of Computations

6) FINE AGGREGATE

Enter specific gravity of fine aggregate (if unknown, use 2 55 to 2 75 for normal weight aggregate) = 2 6

Compute

Weight of fine aggregate = 1295 lb/yd^3

Solid volume of fine aggregate = 7 982 ft^3

Next Step | Previous Step | Start of Computations

7) ADJUSTMENT FOR MOISTURE IN AGGREGATE

Display Design mix water = 340 lb/yd^3

Enter total moisture content in coarse aggregate = 2 %

Enter total moisture content in fine aggregate = 3 %

Enter the degree of moisture absorption of coarse aggregate = %

Enter the degree of moisture absorption of fine aggregate = %

Compute

Net mix water = 269 344 lb/yd^3

Wet weight of coarse aggregate = 1622 106 lb/yd^3

Wet weight of fine aggregate = 1333 85 lb/yd^3

Is water reducer (chemical admixture) used in the mix?

* NO, click here to proceed with regular mix design

* YES, select appropriate input from Table below

If dosage of water reducer is applied as percentage of cement weight, click here	**Enter** this percentage %
If dosage of water reducer is applied as percentage of cementitious materials (cement plus pozzolanic materials) weight, click here	**Enter** this percentage %

Enter percent of reduction in water (as given by the manufacturer) due to applied dosage of water reducer = %

Compute

Adjusted mix water = lb/yd^3

Weight of water reducer = lb/yd^3

Next Step Previous Step Start of Computations

8) SUMMARY OF MIX DESIGN

Enter batch percentage = 5 %

Summarize

Compressive strength at 28 days = 4000 psi

Slump

maximum = 4 in

minimum = 1 in

Nominal maximum size of aggregate = 3/4 in

Water-cement (or water-cementitious materials) ratio = 57

Concrete type is Non-air-entrained

Air content = 2 %

Unit weight of coarse aggregate = 95 lb/ft^3

Ingredients of Concrete Mixture

Water *lb/yd^3*	Cement *lb/yd^3*	Coarse Aggregate *lb/yd^3*	Fine Aggregate *lb/yd^3*	Pozzolanic Materials *lb/yd^3*	Water Reducer *lb/yd^3*
269 344	596 491	1622 106	1333 85		

Ingredients of 5 % Concrete Batch

Water *lb*	Cement *lb*	Coarse Aggregate *lb*	Fine Aggregate *lb*	Pozzolanic Materials *lb*	Water Reducer *lb*
13 467	29 825	81 105	66 693	0	0

Clear all values

New Design | Previous Step | Start of Computations

Contact A Ghaly at ghalya@union edu

A Ghaly Homepage | Engineering Department Homepage | Union College Homepage

Mn/DOT Mix Design

Date 02/23/2011
Time 10 09

American Concrete Products
Item Listing

Page 1

Item Code	Description	Short Descr	8006 No Category	Inventory Item Code	Keep in Inventory	Resale Item	Constituent Item	Use Serial Number	Use Lot Number

Report Selection

Report Sequence Item Code

Item Code	34472465	thru	34472465
Short Description		thru	
Item Category		thru	
Location Code	72	thru	72

Include

[ ] Item Detail	[X] Constituents	[ ] New Page For Each Item
[ ] Cost Information	[ ] Mix & Batching Information	[ ] Batch Code Information
[ ] Pricing Information	[ ] Inventory Information	

Date 02/23/2011
Time 10 09

American Concrete Products
Item Listing

Page 2

Item Code	Description	Short Descr	8006 No Category	Inventory Item Code	Keep in Inventory	Resale Item	Constituent Item	Use Serial Number	Use Lot Number
34472465	3A22AW/A CITY MIX	3A22A W/A	34 000 BR ALL		[ ]	[X]	[ ]	[ ]	[ ]

Constituents		Item Code	Short Descr	Quantity	
72	CENTRAL NEW ULM	CA5NUQQ	3/4 QUARTZITE	1750 00	lb
		SANDNS	SAND NORTH STAR	1150 00	lb
		CEM LEH	LEHIGH MASON CIT	519 00	lb
		FA HW	Flyash Bulk	92 00	lb
		WATER	Water	29 05	ga
		DARAM	DARAVAIR M	7 00	oz
		WRDA82	GRACE WRDA 82	4 00	oz

*** 1 record(s) listed ***